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Programmatic Need for a Zero Emission Steam Technology (ZEST) Research Facility

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Technical Support Document

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Prepared by
Energy and Environment Directorate
Lawrence Livermore National Laboratory

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Contents

Executive Summary

Lawrence Livermore National Laboratory (LLNL) is proposing to construct an on-site research facility for a novel electric power generation system that exploits clean-burning fossil fuels. This system, termed Zero Emission Steam Technology (ZEST), offers unique economic and environmental benefits, including:

- Highly efficient power generation using the most advanced combustion and turbine technologies.
- Ability to burn a range of fossil fuels, including natural gas, synthetic gas from coal ("coal syngas"), and coal-bed methane.
- No oxides of nitrogen generated that would contribute to air pollution.
- No greenhouse gases emitted.
- Secure geologic sequestration of the carbon dioxide (CO_2) combustion product.
- Use of the CO_2 combustion product to enhance oil recovery in mature fields.

The proposed research facility will provide a necessary step toward commercialization of ZEST. Despite the technology's promise, it *will not be implemented by the U.S. electric power industry unless an agency such as DOE takes on the task of demonstrating its scientific and economic viability.* The U.S. electric power industry typically requires 50,000 hours of operational data—nearly six years of continuous duty—before investing in a major new technology.[1] Hence, there is a strong programmatic need for DOE to provide such data for ZEST, to accelerate commercial investment in this technology.

The ZEST combustion process is based on rocket engine technology. It burns pure oxygen with a hydrocarbon fuel under stoichiometric conditions to produce power with virtually no oxides of nitrogen generated. The flexibility of ZEST's gas generator, which has independent temperature and pressure control, will allow modular upgrading of turbine systems as new, more efficient technology becomes available. It is envisioned that the ZEST research facility will serve as a testing laboratory for new turbine technology being designed by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) Next Generation Turbine Program.

[1] Personal communication between Clean Energy Systems and General Electric Power Systems.

In its initial phase, ZEST is expected to operate at 35% efficiency, using commercially available turbine technology, while future phases of the ZEST system should approach an operating efficiency of 60% and, based on $6 per GJ of natural gas, should generate electricity for less than 6 cents per kilowatt-hour. ZEST is expected to be competitive with or surpass all other fossil fuel power generation technologies in efficiency and economy of operation when CO_2 sequestration is included. When the sequestration is carried out in a mature oil field, significant additional energy can be derived from the supplementary oil recovered. For every Btu of energy generated through combustion in the ZEST gas generator, sufficient oil to produce as much as *five* Btu of energy can possibly be recovered.[2]

The ZEST research facility will demonstrate the advantages of building multi-objective power plants that not only generate emission-free electricity but that also use their CO_2 combustion products to enhance oil recovery at combined power and fuel production sites around the United States. LLNL is the logical host for such a research facility for several reasons, including staff expertise in research areas that are key to successful development of ZEST. These areas include ceramic membrane oxygen separation, thermal barrier coating development for high-temperature steam turbines, computational simulation of combustion processes and geologic CO_2 sequestration, geophysical imaging and analysis, and CO_2 injection to enhance oil production in seismically active basins. Equally important, LLNL has an impressive track record of successfully translating complex systems from bench-scale proof-of-concept to field-scale prototype.

LLNL also has a valuable combination of site and regional attributes, including close proximity to both a mature oil field and deep saline aquifers. This setting presents an opportunity to establish—as an integral component of ZEST—a U.S. geologic sequestration research facility that explicitly integrates advanced modeling and field studies of CO_2 injection for both enhanced oil recovery *and* pure environmental isolation. Important regional attributes include strong San Francisco Bay Area support for clean energy and environmental technologies, ready access to multiple power grid feeds, a controllable nearby base load, and a highly stressed local grid that will benefit from a nominal 10-MW addition. LLNL also enjoys an established collaboration with the larg-

[2] Based on LLNL calculation, which assumes that two barrels of oil can be recovered for each barrel of CO_2 injected.

est research university in the country and has geographical proximity to many important technology developers.

Collaborations with other DOE national laboratories will be important for the success of ZEST. LLNL will draw upon NETL's Next Generation Turbine (NGT) Program and its industrial partners as resources for the design and testing of high-temperature steam turbines, which are critical for achieving ZEST's high efficiency potential. NETL will provide vital expertise and testing facilities for expanding ZEST's capabilities to include the use of coal syngas fuel, and will lead the design and testing effort for a syngas-compatible reheater. In addition, Oak Ridge National Laboratory's High Temperature Materials Laboratory (HTML) capabilities will be critical for evaluating LLNL thermal barrier coatings for corrosion rates at elevated temperatures.

The goal of the proposed project is to exploit the unique convergence of LLNL's research capabilities and its geologic and geographic setting to:

- Demonstrate ZEST's performance, thus enabling its emergence in the marketplace.
- Establish a U.S. research facility for geologic CO_2 sequestration, which will provide a much-needed testbed for evaluating DOE-proposed sequestration strategies.

ZEST research facility design and construction activities will span six years and will cost a total of about $70.2 million (see Table E.1).

Table ES-1. Major ZEST Funding Elements
(3Q FY01 $ Million)

Total estimated cost (TEC)	**$ Million**
Design and engineering	7.6
Project management	4.1
Construction management	4.7
Construction	48.9
Subtotal TEC	**65.4**
Other project costs (OPC)	
Conceptual design	0.6
Hazards, analysis, NEPA (EA), & permits	0.3
Risk reduction engineering	3.0
Misc. other costs	0.9
Subtotal OPC	**4.8**
Total project cost (TPC)	**70.2**

In addition to constructing and operating the power plant research facility, critical activities will include development of the novel technologies, simulations, and analyses important for the success of ZEST. The estimated budget for these activities in FY05 is $4.75 million.

1. The ZEST Concept

Lawrence Livermore National Laboratory (LLNL) is proposing to construct a Zero Emission Steam Technology (ZEST) research facility on site that will implement advanced technologies for efficient electric power generation from fossil fuels and for the secure geologic sequestration of CO_2.

The main objective of ZEST is to demonstrate the scientific and economic viability of fossil fuel power production without environmentally detrimental atmospheric emissions. A secondary aim is to demonstrate the practicality of a multiple-objective power plant—one that produces emission-free electric power while using a combustion product to enhance oil recovery in a mature oil field.

ZEST offers tremendous potential for environmentally friendly distributed power and enhanced oil recovery applications at many combined fuel production sites around the country. The research proposed for advancing geologic sequestration science will also allow generalization of siting to areas with deep saline aquifers—not just those near active oil fields.

2. Why A ZEST Research Facility Needs to Be Built

Zero Emission Steam Technology facilities offer many environmental and economic benefits. Traditional power generation from fossil fuels results in problematic air emissions that contribute to greenhouse-gas emissions and add to photochemical smog formation. In contrast, ZEST facilities offer environmentally friendly electric power generation that is also highly efficient and cost-effective, especially since the process exhaust will be used to enhance oil production in mature fields. *However, ZEST will not be commercialized unless the federal government takes on the task of demonstrating its scientific and economic viability.* The U.S. electric power industry is a conservative community and is notably risk-averse regarding the construction of plants based on new technologies with unproven reliability and performance. The industry typically requires 50,000 hours of operational data—nearly six years of continuous duty—on a new power generation technology before it is willing to invest in that technology.[3] Hence, there is a strong need to provide such data for Zero Emission Steam Technology, which will accelerate commercial investment in this process.

The power industry will require answers to questions such as:

- What is the mean time to failure for the ZEST system, and in particular, for its gas generator?
- What is ZEST's maximum turn-down ratio (maximum/minimum output) with stable combustion?
- What are the technology's failure modes?
- What are its maintenance requirements?
- When will efficiency improvements be available?
- What noise issues or other "nuisance" impacts are associated with the technology?
- How effective are the high-speed controls that will be installed to insure safe operation?

Only after these questions have been answered and the technical risks well characterized will industry consider making major investments in ZEST power plants. Thus, building the ZEST research facility is on the critical path to commercialization.

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[3] Personal communication between Clean Energy Systems and General Electric Power Systems.

The ZEST facility also will provide a much-needed testbed for addressing key environmental concerns regarding safe disposal of CO_2 waste streams. In the report, *Carbon Sequestration: Research and Development* (December 1999), DOE has outlined the fundamental scientific questions that must be answered to develop sound geologic sequestration policies and regulations:

- What is the *net* sequestration attainable by injecting carbon dioxide into hydrocarbon reservoirs to enhance oil recovery?
- What is the ultimate capacity and isolation security of geologic formations targeted as pure storage reservoirs for carbon dioxide waste streams?
- What "screening" criteria can be used to quantify "net sequestration," "ultimate capacity," and "isolation security" for specific geologic formation types?
- How can these screening criteria be translated into appropriate regulations for generalized geologic sequestration?

These fundamental questions can only be answered in the context of a comprehensive research program that explicitly integrates advanced computational simulation capabilities and well-characterized field studies. LLNL's expertise in modeling geologic CO_2 sequestration, LLNL's unique geologic setting, and the CO_2 waste stream captured from ZEST together present a unique opportunity to establish a U.S. geologic sequestration research facility, which is an integral part of this project. The United States needs such a facility, because of its critical importance in developing U.S. carbon sequestration policy.

The goal of the proposed project is to take advantage of the unique convergence of advanced technologies and geologic setting at LLNL to (1) demonstrate ZEST's performance, thus accelerating its emergence in the marketplace; and (2) establish a U.S. geologic sequestration research facility, which will fill DOE's existing void in this area.

3. What Is New and Innovative About ZEST?

3.1 The Gas Generator: Modular Rocket-Engine-Inspired Design and Independent Parameter Control

Zero Emission Steam Technology borrows its gas generator design from rocket engines that have been reliably sending payloads into space for decades (see Figures 1 and 2).[4] By so doing, significant environmental impacts are avoided. Conventional power plants rely heavily on emission-control devices that are expensive and only partially effective in removing nitrogen oxides and, in the case of coal- and oil-fired plants, particulates and oxides of sulfur from the waste gas stream. Many of these conventional plants have been forced to shut down because of environmental constraints.

ZEST is a *pollution-prevention* approach to the problem of air emissions that accompany conventional power plant operations.

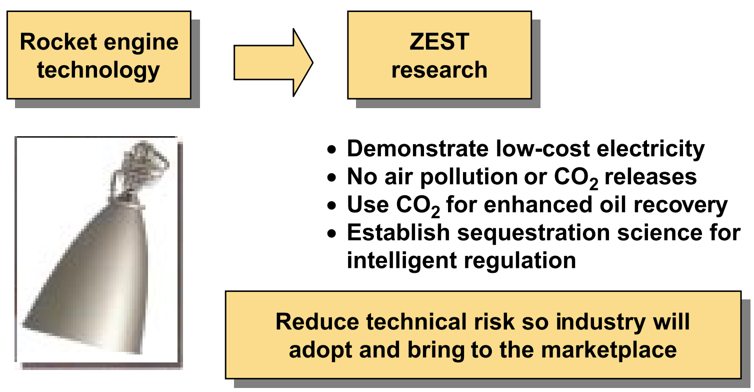


Figure 1. Applying rocket engine technology to power production and CO_2 sequestration.

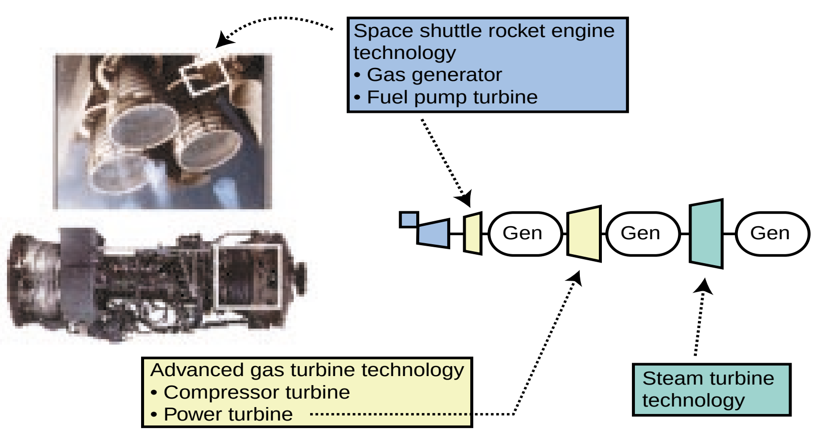


Figure 2. The ZEST gas generator and high-pressure turbine are based on rocket engine technology, while advanced turbine concepts contribute to the design of ZEST's intermediate pressure turbine.

[4] Gas generator design will be based on the intellectual property of Clean Energy Systems (CES), a new spin-off company composed primarily of former Aerojet engineers.

The ZEST concept does not rely on "back-end" mitigation measures but rather on a process that by its basic design *does not create* air pollutants. Combustion is carried out under stoichiometric conditions, burning either natural gas, synthetic gas from coal ("syngas"), or coal-bed methane, with high-purity oxygen separated from the air (see Figure 3). Because oxygen, rather than atmospheric air, is used in the combustion process, no nitrogen reactions occur, and thus no nitrogen oxides are generated. Large quantities of water are added to control temperatures, producing high-energy steam without emissions. ZEST power plants will also produce several potential revenue-generating products, including industrial gases such as carbon dioxide, argon, oxygen, and nitrogen. In addition, if the ZEST gas generator is run in the fuel-rich mode, it will generate hydrogen, which can be separated from the combustion products for use in fuel-cell-powered automobiles[5] (see Figure 4).

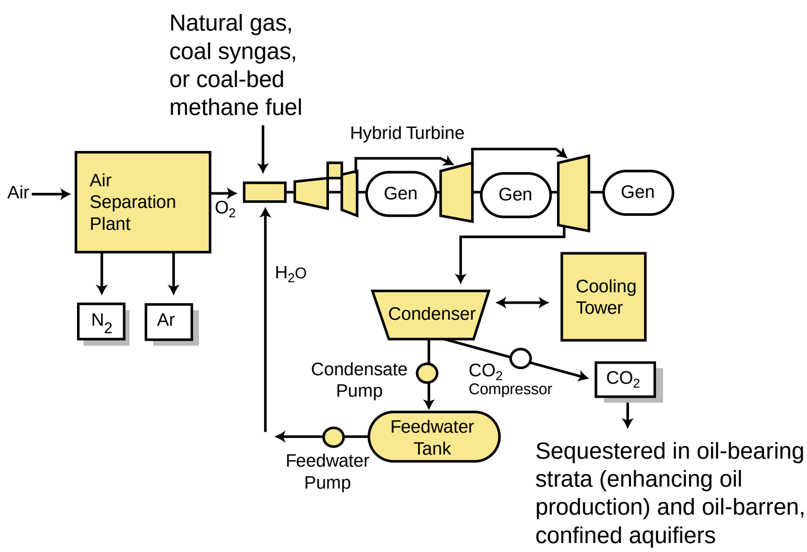


Figure 3. The Zero Emission Steam Technology power plant concept. Oxygen is burned with natural gas, coal syngas, or coal-bed methane to produce electric power devoid of NO_x emissions. All CO_2 generated during combustion is sequestered in oil-bearing and oil-barren geological formations.

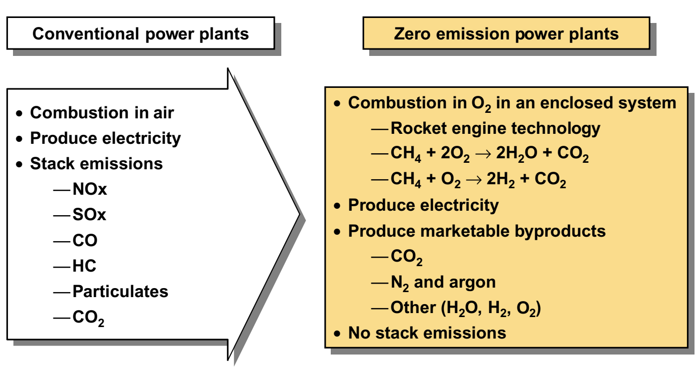


Figure 4. ZEST represents a paradigm shift in power plant design.

[5] Developing commercial hydrogen generation from a ZEST process would require a major research effort not addressed in the scope of the proposed project. The potential for hydrogen embrittlement of turbine blades and the costs of developing hydrogen separator equipment would have to be evaluated.

The gas generator developed by Clean Energy Systems (CES) for ZEST will be able to independently control pressure and temperature of the working fluid. Pressure will be regulated by adjusting the mass flow rate of fuel and oxidizer. Temperature will be lowered as needed through the addition of water to both the primary combustion zone and the downstream cool-down sections. This independent control feature allows gas generator output to be matched to *any* available steam-turbine technology, enabling ZEST to be upgraded as new state-of-the-art components become available. Each turbine can either be coupled to its own generator, with power from the different generators electronically combined, or all turbines could drive a common gearbox connected to a single generator. The ZEST research facility will use the separate turbine generator configuration to allow independent upgrades of the high-pressure, intermediate-pressure, or low-pressure turbines.

Currently available commercial steam technology for power plants operates at approximately 1100°F (593°C) and will be used unless higher-temperature, more efficient technology becomes available by the time that construction of the ZEST research facility begins. Boeing Rocketdyne and Pratt-Whitney, for instance, build turbines for the space shuttle's main engine fuel pumps that operate at 1400°F (760°C). If available, a derivative of this turbine will be used as the high-pressure turbine for the initial ZEST facility. A derivative of combustion turbine design may also be available for use as ZEST's intermediate turbine. If available in the initial phase, implementing these turbines could raise the efficiency of electrical power generation to 45–50%, instead of the estimated 35% attainable from current commercially available steam turbines.

Because of the success of the NETL Advanced Gas Turbine Program, state-of-the-art combustion turbines are being delivered with inlet temperatures of 2550°F (1400°C). A goal of ZEST is to implement steam turbines into its process that achieve similar temperature-performance. ZEST will work closely with NETL's Next Generation Turbine (NGT) Program, which is expected to meet the technical challenge of upgrading steam turbines to gas turbine temperature-performance levels.

Once ZEST is commercialized, the flexibility of its CES gas generator temperature and pressure controls will allow distributed, small-scale plants (30–100 MW) to be upgraded to higher efficiencies as commercially viable turbine improvements pen-

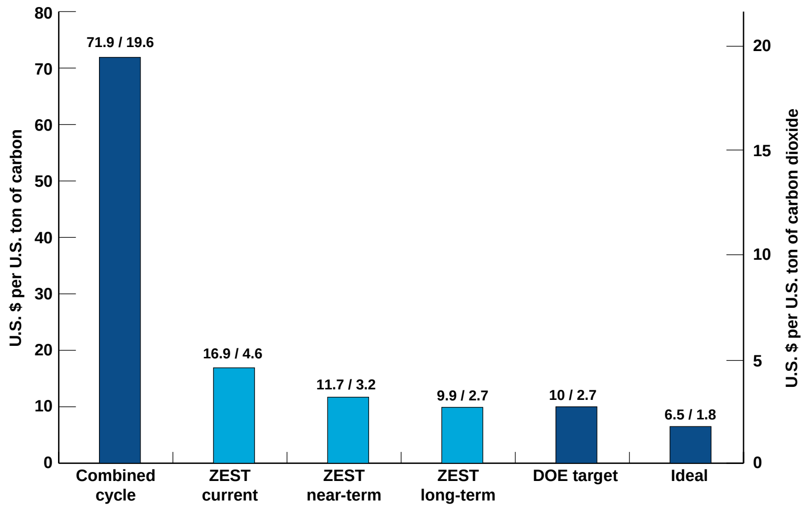


Figure 5. Comparative cost of geologic carbon sequestration for 100-MW plants. The left-hand column shows cost per ton of carbon; the right-hand axis corresponds to cost per ton of CO_2.

etrate the marketplace. This could be accomplished without changing other major components of the plants.

Besides offering powerful operational and environmental advantages, ZEST has the potential to generate power at cost-per-kilowatt-hour rates that are competitive with or surpass all other technologies. Note from Figure 5 that the cost of geologic sequestration per ton of carbon generated by a ZEST plant ($10 to $17) is expected to be far lower than the cost for a combined-cycle plant, which is estimated at about $72.[6] This is because of the high cost of CO_2 separation required by the combined-cycle plant. A detailed discussion of Figure 5 can be found in Appendix A.

We envision that the ZEST Phase II and Phase III upgrades will use more advanced turbine technology than is currently available. As seen from Figure 6, Phase II technology plants are envisioned to operate at 45–50% efficiency and to generate electricity at approximately 7 cents per kilowatt-hour, based on a natural gas cost of $6/GJ. The Phase III plants will be designed to operate at 60% efficiency and to generate power for about 6 cents per kilowatt-hour. All phases of ZEST plants will sequester CO_2 in geologic formations. Note from Figure 6 that for other power-generating technologies, costs both without sequestration (black symbols) and with geologic sequestration (green symbols) are given.

[6] The estimate for combined cycle plants may in fact be conservative. Dr. Chuck Schmidt, NETL Program Manager for Geologic Sequestration, noted in a private communication that the estimate in Figure 5 of about $72 to geologically sequester one ton of carbon generated in a combined-cycle plant was more likely $110 per ton, which would make the difference in sequestration costs even greater between ZEST and combined-cycle plants.

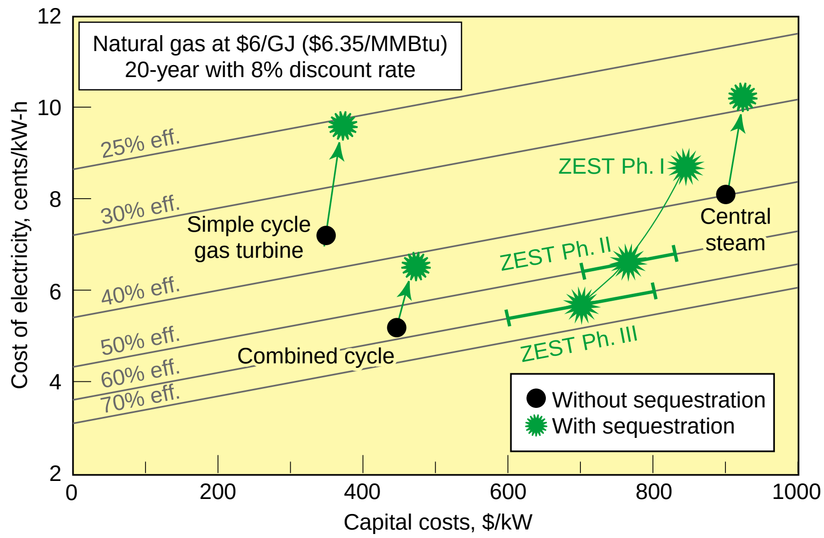


Figure 6. Economic comparisons of existing technologies and ZEST, with and without geologic carbon sequestration, for 200- to 300-MW plants. When sequestration is considered, the ZEST Phase III cost of electricity is lower than for competing technologies. This chart shows only fuel costs and capital costs. Maintenance and operating costs are not included.

If the costs of CO_2 sequestration are not considered, combined-cycle plants may appear to be the best technology choice, because they generate electricity at approximately the same cost and efficiency as the ZEST Phase III design but with half the capital cost per kilowatt. Once CO_2 sequestration costs are included, however, the picture changes. The combined-cycle performance is significantly impaired; its kilowatt-hour cost rises to over 6 cents, and its efficiency slips to 43%, because of its high cost for CO_2 separation and sequestration. The ZEST Phase III technology, on the other hand, is expected to approach 60% efficiency, with cost of electricity about 6 cents per kilowatt-hour. Although a ZEST facility's capital costs are higher, these would be amortized by the lower operating costs.

3.2 Coupling Oilfield Production Facilities with Distributed Electric Power Generation Plants

For every barrel of crude oil produced in the United States, approximately two barrels remain in the ground. However, this historical one-third yield can often be improved through modern techniques of enhanced oil recovery (EOR). CO_2 flooding has proven to be a particularly effective and economically attractive EOR methodology for suitable reservoirs located sufficiently proximate to natural CO_2 sources. Implementation of this technique, however, has been severely limited—primarily to the Permian Basin of west Texas—by the sparse occurrence of adequate CO_2 reserves. ZEST technology offers a win-win solution to this supply problem by providing a low-cost source of CO_2 for local

EOR while eliminating CO_2 emissions from direct power generation.

The onshore oil and gas fields of the contiguous United States constitute a mature oil and gas province. Oil production in this region peaked in the early 1970s and has declined since then. Each year, more than 15,000 marginal oil and gas wells are abandoned, and 220,000 nonproducing wells are "idled." It is important for our country to combat our currently declining oil production rate. If possible, we must reduce the rate at which our domestic oil fields are being abandoned. Once a field is "shut in," it cannot be economically restored. The ZEST project offers hope of further exploiting many of these mature fields and deriving significant additional energy from the supplementary oil recovered. LLNL estimates have shown that for every Btu of energy generated through combustion in the ZEST gas generator, sufficient oil can be recovered to produce up to *five* Btu of energy.[7]

3.3 Establishing a Research Facility for Geologic Carbon Dioxide Sequestration

The United States has a critical need to answer key scientific questions regarding geologic CO_2 sequestration, a concept presently forecast to occupy a prominent, perhaps leading, role in the country's 21st-century carbon management. The questions outlined in Section 2 can only be addressed following integrated development of computational modeling tools and field tests to formulate the requisite advanced simulation capabilities. Ideally, such development will be centralized at a site such as LLNL that has the capability to carry out both the modeling work and the necessary field studies. The ZEST project offers the opportunity to establish a unique U.S. geologic sequestration research laboratory at a facility such as LLNL.

[7] This estimate assumes that two barrels of oil can be recovered for each barrel of CO_2 injected.

4. How ZEST Supports the National Energy Policy

The *National Energy Policy* document[8] released in May 2001 stresses the importance of advancing "new, environmentally friendly technologies to increase energy supplies and encourage cleaner, more efficient energy use." The ZEST system is intended to meet each one of these challenges. By burning pure oxygen in its gas generator, ZEST will avoid the generation of oxides of nitrogen air pollution, which the *National Energy Policy* report specifically mentions as needing to be controlled. By sequestering all CO_2 combustion products, ZEST will eliminate contributions to global warming. And by sequestering this CO_2 in oil-bearing strata, ZEST will enhance oil recovery and extend the lifetimes of shallow, mature fields that otherwise might have to be closed down. Finally, through its use of cutting-edge turbine and combustion technology, ZEST will produce electricity that is competitive in price with the most advanced fossil-fuel-based power generation technologies.

The *National Energy Policy* recommendations recognize the importance that coal must play in our energy future. Coal is the United States' most abundant fuel source. We have a 250-year supply of coal, and it is expected to remain the dominant fuel for meeting electricity demand through 2020. ZEST is designed to make good use of our plentiful coal reserves. The ZEST gas generator can burn synthetic gas from coal as well as coal-bed methane. The ZEST gas generator can also burn natural gas, our third-largest power source for electricity generation.

[8]This section responds to policy recommendations made in the document, *National Energy Policy: Reliable, Affordable, and Environmentally Sound Energy for America's Future*, a report of the National Energy Policy Development Group, ISBN 0-16-050814-2, May 2001.

5. How ZEST Supports the DOE Fossil Energy Mission

The mission of DOE's Office of Fossil Energy includes enhancement of U.S. economic, energy, and environmental security through:

- *Conducting energy-related research that promotes efficient, environmentally sound fossil fuel production and use.* The goal of ZEST is to develop high-efficiency power generation from fossil fuels with minimum environmental impact. ZEST will operate with virtually no air emissions that add to either air pollution or global warming and will use CO_2 gas produced in its combustion process to enhance oil production from mature petroleum reserves.

- *Partnering with industry to advance fossil energy technologies toward commercialization.* ZEST will involve a close partnership with Clean Energy Systems (CES) Inc. to develop rocket-engine-based gas generator technology for electric power generation. LLNL will also work with another industrial partner, such as Praxair or Air Products, to develop an economical, efficient ceramic membrane approach for oxygen separation from atmospheric air.

- *Developing innovative strategies for secure nonatmospheric disposal of CO_2 waste streams associated with energy production.* Geologic sequestration—either in the context of injection for enhanced oil recovery or pure isolation—represents one of the most promising CO_2 disposal strategies. A unique U.S. geologic sequestration research facility—one that integrates advanced modeling *and* field characterization of *both* EOR- and storage-based implementations—will be established as an essential component of the ZEST project.

DOE'S Office of Fossil Energy recognizes that coal, oil, and natural gas are all indispensable elements of our country's energy mix. Because of its abundance and low cost, coal is now used to generate more than half of the United States' electricity.[9] One quarter of all the world's coal is found within the United States.

[9]Statement of Robert S. Kripowicz, Principal Deputy Assistant Secretary for Fossil Energy, U.S. Department of Energy, to the Subcommittee on Energy and Power, Committee on Commerce, U.S. House of Representatives, 8 June 2000.

Because dependence on clean coal technologies is vital to the United States' future energy strategies, the ZEST facility will be designed to use coal syngas as an alternative to natural gas in its combustion process.

The ZEST project supports the mission of the Office of Fossil Energy's National Energy Technology Laboratory, which is to solve U.S. energy and environmental problems through conducting, partnering in, and procuring research, development, and demonstration projects to advance fossil energy technology into the commercial marketplace. NETL's aims include developing technologies that also contribute to U.S. employment and to the advancement of U.S. industries in the global market. NETL's mission leads to various strategies that will be aided by ZEST, including:

- *Increase economically recoverable domestic oil supplies to reduce future import dependence.* The ZEST project aims to increase petroleum production from mature fields by demonstrating the scientific and economic feasibility of multiobjective power plants that provide low-cost CO_2 for enhanced oil recovery in local mature oil fields.

- *Develop innovative methodologies and modeling tools for evaluating CO_2-flood effectiveness in terms of oil production and CO_2 sequestration.* ZEST will make use of cutting-edge reservoir modeling and imaging technologies being developed at LLNL and the National Petroleum Technology Office (NPTO, now an office of NETL).

- *Identify and develop new fossil energy technologies that significantly reduce greenhouse gas emissions.* The main goal of ZEST is to produce emission-free power from fossil fuel, using a novel approach based on rocket engine technology. In particular, all CO_2 generated from the combustion process will be sequestered geologically, by dual injection either into a relatively shallow hydrocarbon reservoir (to enhance oil recovery) or a relatively deep confined aquifer (for pure isolation). Hence, this waste stream will not contribute to atmospheric greenhouse gas concentrations or global warming.

NETL has recognized the potential benefits of ZEST and is currently funding a first-generation 10-MW gas generator demonstration. This \$2.6 million project is a critical-path experiment for ZEST development that also supports NETL's Vision 21 program. As part of ZEST project hardware development, NETL will initiate the design, construction, and testing of a coal syngas reheater that will increase plant efficiency by raising the temperature of the working fluid between turbine stages.

6. ZEST Technical Details

6.1 Oxygen Separation

ZEST's combustion process requires a continuous stream of oxygen of at least 95% purity, but preferably higher. Most of the ZEST facility's oxygen requirements will be met through construction of an on-site cryogenic distillation oxygen separation plant.

Other approaches besides cryogenic distillation were examined for supplying oxygen. Vacuum pressure swing adsorption (VPSA) processes were considered for the oxygen plant, but these generally cannot furnish an oxygen stream of greater purity than 90–93%, with nitrogen making up much of the impurities. This would result in production of unwanted oxides of nitrogen in ZEST's gas generator, and the greater gas flow required for a VPSA plant would increase equipment sizes and costs. Also considered was an option to operate ZEST without an oxygen plant, relying instead on storage tanks with oxygen delivered by truck. Although capital costs would be lower for such a system, run-out costs would be considerably higher than for a cryogenic plant operating for 10 or more years. Also, relying on stored oxygen was estimated by LLNL staff to require 12 tank trucks of oxygen per day, and the logistics of managing such a supply system would be very difficult.

The oxygen separation process will be constructed adjacent to the building housing ZEST's gas generator, turbines, and electric generators, as illustrated in Figure 7.

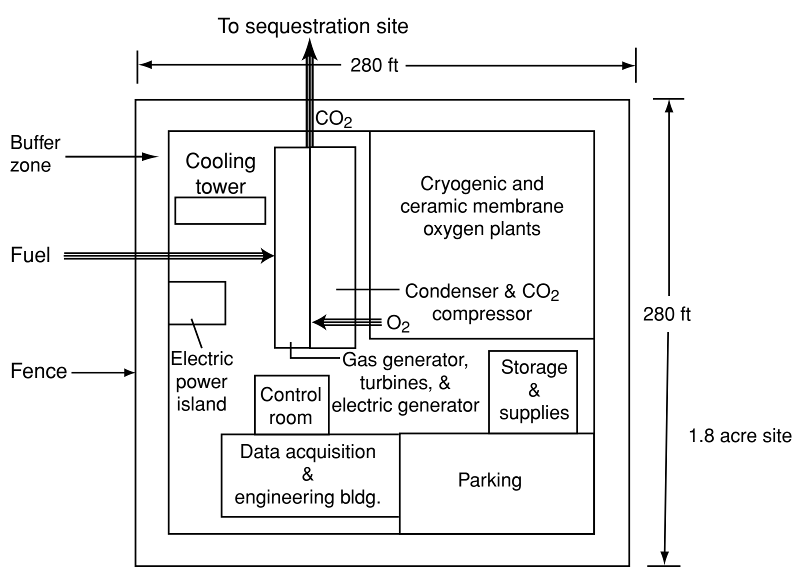


Figure 7. ZEST's research power plant will be built on a 1.8-acre site at LLNL.

Notice from Figure 7 that two types of separation techniques will be employed. Although cryogenic techniques will provide approximately 90% of ZEST's oxygen needs, a novel membrane separation technology will also be used. An important ZEST research area will be to develop high-temperature ceramic membrane materials that can provide more energy-efficient, less-expensive oxygen generation than is currently available. The ceramic membrane plant will include research stations for testing and monitoring the performance of membranes under development. This effort may be accomplished in partnership with a commercial manufacturer of oxygen, such as Praxair or Air Products. These companies are currently working with NETL on novel (proprietary) oxygen transport membranes.

Membrane technologies are not new to the field of gas separation. Polymeric membranes have been commercialized, but are used primarily for nitrogen production, as well as for hydrogen and CO_2 separation. Polymeric membranes can also separate oxygen from air, although their selectivity is low. They typically generate an oxygen stream that is only 30% to 40% pure, with nitrogen comprising most of the remainder. Such low purity is not acceptable for ZEST's combustion process because of the large quantity of nitrogen oxides that would be generated. Oxygen generation from polymeric membranes is also expensive, as compared to nitrogen production.

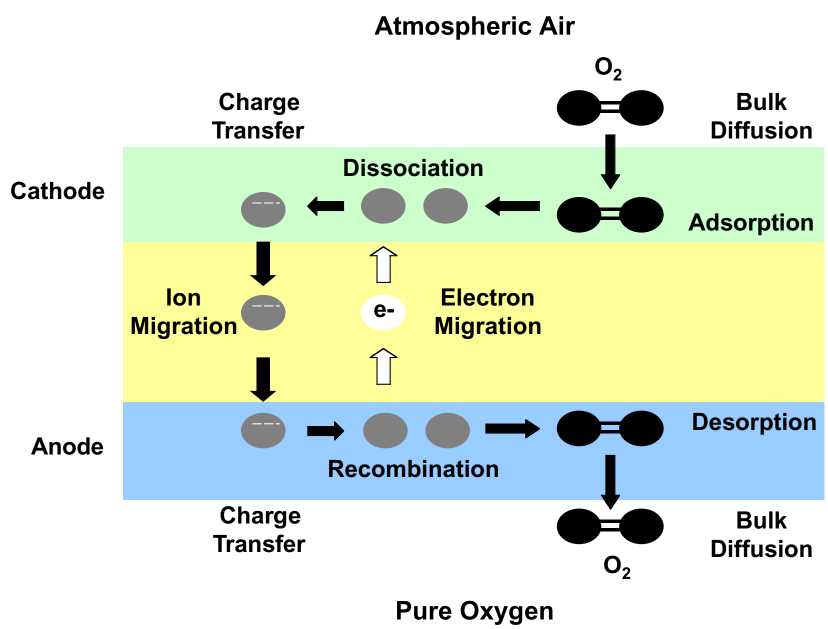


Figure 8. Ceramic membrane oxygen transport technology provides a means of generating pure oxygen for combustion. The membrane selectively removes oxygen from atmospheric air. (Source: Ravi Prasad, Minish Shah, Ray Drnevich, and Dave Thompson, OTM—A Novel Technology for Integrated Oxygen Production, Copyright 2000 Praxair Technology, Inc. Prepared with support of U.S. DOE under Contract No. DE-FC26-99FT40437.)

Ceramic membranes show much more promise than polymeric membranes for high-purity oxygen separation and are the target of intense research at LLNL as well as at other locations around the country. Ceramic membranes transport oxygen by a vacancy diffusion mechanism, which is analogous to the way that semiconductors transport electric current (see Figure 8). The ceramic membrane is comprised of a doped crystal lattice with properties such that oxygen is the only gas in atmospheric air that can occupy holes in the lattice. As a result, ceramic membranes have a very high selectivity for oxygen and can produce it at a very high purity. The oxygen chemical potential difference across the membrane provides the driving force for oxygen permeation. As shown in Figure 8, O_2 molecules adsorb on the cathode side of the membrane, dissociate into atoms, and then pick up electrons to become oxygen ions. These ions travel from the side of the membrane with high-oxygen partial pressure to the low-oxygen partial pressure (anode) side by repeatedly jumping from their lattice sites to adjacent vacancies. On the anode side, the oxygen ions give up their electrons to become atoms, then recombine into O_2 molecules that desorb from the membrane into a gas phase. Electrons from the membrane's anode side move toward the cathode side to complete the circuit.

Limiting factors in oxygen transport through the membrane include (1) the ability of oxygen to cross a boundary layer; (2) the rate of surface oxygen exchange; and (3) the diffusion rate of oxygen ions and electrons through the membrane itself. The high operating temperatures of ceramic membranes, 600 to 1,100°C, result in fast oxygen transport rates and quick separation. This characteristic of the membranes makes them potentially more cost-effective than standard cryogenic separation techniques. The maturity of the ceramic membrane technology is such that it could possibly be included in an oxygen plant that begins operation in FY 2004 or later. Its cost of operation could be reduced if process heat from the ZEST facility's gas generator were used to maintain the membrane at its 600 to 1,100°C operating temperature.

6.2 Control System

For safety and reliability, the ZEST power plant's startup, operation, and shutdown must be automatically controlled. The automatic system needs to supply the gas generator with an inert purge gas during startup, then deliver precise flows of natural gas, oxygen, and water during combustion. The switching from purge gas to reactive gases and cooling water has to be fully automated. Appropriate sensors need to be installed to detect unsafe operating conditions and activate automatic shutdown if necessary. A backup control system is required to insure safe shutdown of the plant in the event of an emergency. Backup power must be available to deliver electricity to the control system to insure safe shutdown during an emergency.

Planned work in FY01 includes plant simulation, which will provide the basics for designing the automated control system. This effort will build on the experience of the prototype 10-MW gas generator project currently under development by CES, using NETL and in-kind funding.

6.3 Gas Generator

The gas generator, which will be purchased from LLNL's industrial partner, Clean Energy Systems, Inc., is the critical component in the power plant's operation. It will produce the hot gases for powering the series of turbines connected to electrical generators. The gas generator is essentially a land-based rocket engine designed to burn fossil fuel under stoichiometric conditions. Although natural gas will be used in the ZEST facility, an advantage of the CES gas generator is that it can burn virtually any gasified fossil fuel that is composed primarily of carbon, hydrogen, and oxygen, including coal-bed methane and coal syngas, with independent temperature and pressure control to match available steam turbines. The fuel will be burned with oxygen that is at least 95% pure, with argon composing the remaining 5%. Combustion will generate gases that are predominantly steam and CO_2.

A 10-MW gas generator is to be demonstrated by CES in FY01. The ZEST Research Facility will utilize the next-generation CES gas generator by building on the results of the first unit. LLNL staff expertise in thermal barrier coatings will be important for development of new internal coatings for extended-use gas-generator surfaces. Rocket engines are typically run for short periods of time, but a gas generator used for continuous power generation must have surfaces able to withstand elevated temperatures for years of continuous operation. Successful thermal barrier coatings in the gas generator could reduce its overall cost by allowing the use of lower-cost structural materials.

The adiabatic flame temperature of the combustion products is approximately 5,600˚F (3,100˚C). Injection of demineralized water, preheated by circulation through the combustor's walls, will result in a CO_2/steam working fluid with a temperature of no more than 3,200˚F (1,800˚C) and a pressure not higher than 3,200 psi (22 MPa). Temperature will be controlled through adjustments in cooling-water flow rate. Because no fuel-rich regions exist in the gas generator, no particulate emissions or smoke will result from combustion.

Additional water will be injected into the exhaust gases from the gas generator combustion chamber because no available turbine can handle 3,200˚F steam. The water will be added in six cool-down modules that have been carefully designed, taking flow rates and residence times into account to permit time for the kinetically-controlled reassociation of carbon monoxide into CO_2. The working-fluid temperature will be gradually lowered in the series of cool-down modules. Temperature and pressure of the working fluid will be adjusted so that it leaves the gas generator meeting the specifications of the high-pressure turbine. In the Phase I ZEST plant, the working fluid will exit the gas generator at 1,050°F and 1,200 psi, while in later phases that use more advanced turbines, temperature will be increased for higher efficiency. As it exits the gas generator, the working fluid will consist of roughly 90% by volume of steam and 10% by volume of CO_2. As depicted in Figure 9, the exact H_2O/CO_2 ratio will depend on the required turbine inlet temperature. Lower temperatures will require fractionally more water added. Because of the range of possible water/CO_2 temperatures, some fundamental research and optimization needs to be performed early in the project. The data from this effort will influence not only working fluid temperatures but also final turbine nozzle and blade designs.

The components of ZEST's gas generator are depicted in Figure10. The *injector body* consists of an Inconel-625 forging that premixes the fuel and oxygen reactants prior to injection into the combustion chamber. Impinging reactant jets create a mixing

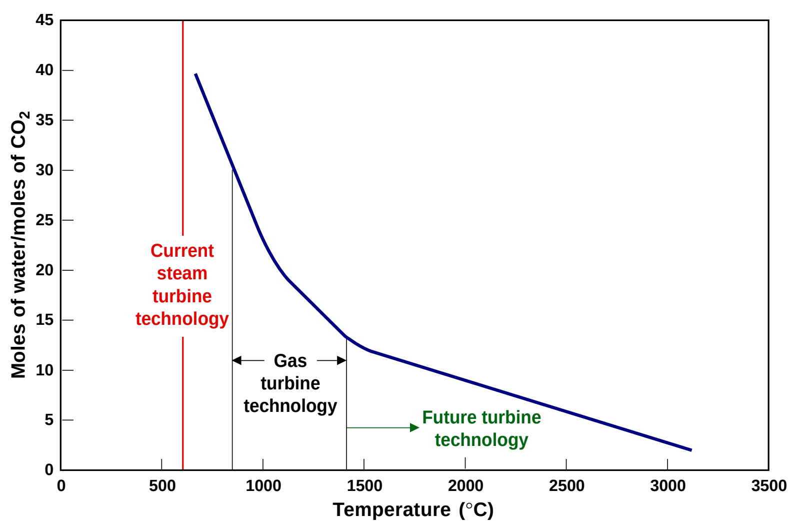


Figure 9. Working fluid turbine inlet temperature vs. water/CO_2 ratio. More advanced turbines that will be installed in the future will employ working fluids with higher temperatures and less water.

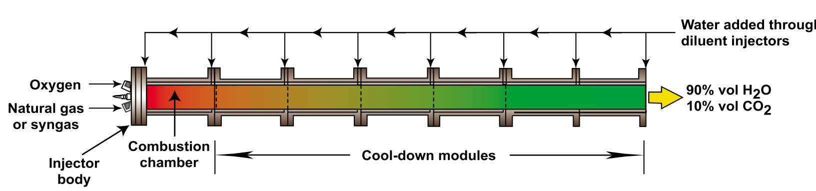


Figure 10. ZEST's gas generator can burn a variety of fuels to generate a working fluid devoid of oxides of nitrogen.

environment within the injector body, while check valves prevent accidental fuel and oxygen backflows. Injector elements within the injector body receive the precisely mixed fuel. These injector elements consist of a stack of diffusion-bonded Inconel-600 platelets with chemically-etched passageways. (Figure11 contains an enlarged drawing of a platelet section for a 10-MW combustor.) Note that cooling water is also introduced into the platelet passageways to control temperatures. The *igniter*, mounted inside the injector body, contains a spark ignition system to initiate combustion.

The gas generator's *combustion chamber,* constructed of a Monel K-400 water-cooled liner and a high-strength steel structural housing, is relatively small for a 10-MW generator—only 12 inches in length, with a 4-inch inner diameter. Coolant water enters the chamber liner at the output end of the chamber and exits at the fuel/oxygen injection end into the injector body.

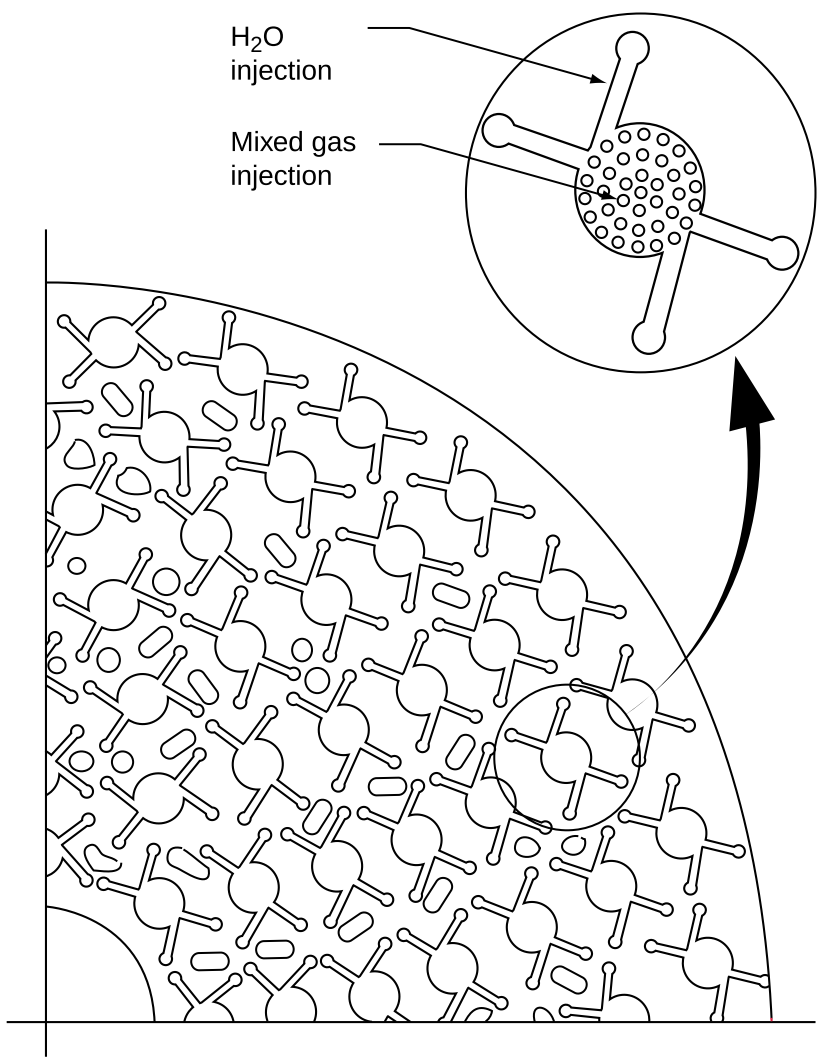


Figure 11. Quarter section of an injector element.

Six *cool-down modules* follow the combustion chamber, each of which is nearly identical to the chamber, to minimize manufacturing costs. The combustion chamber and cool-down module liners consist of slotted walls containing 100 coolant slots. *Diluent injectors* located at the upstream end of each cool-down module add controlled amounts of highly atomized water, in order to optimize working fluid parameters. The coolant flows "upstream" through the chamber liners—i.e., counter-current to the flow direction of exhaust gases, so that the coolant flows into successively higher-temperature modules. Coolant flow rate, pressure, and temperature are all adjusted to keep the coolant in liquid phase for maximum cooling efficiency and to precisely maintain gas/side wall temperatures at levels that will achieve long gas-generator and turbine operating lives, while maintaining high plant efficiency.

The ZEST gas generator is considered to be the highest risk item in the power train. Before construction of the ZEST facility begins, an important activity will be to reduce the technical risk of gas-generator failure. Using characterization-science techniques developed for LLNL's Yucca Mountain and Stockpile Stewardship programs, methods will be devised for employing short period (0.5 hour to 10 hour) gas generator testing to detect submicron-level erosion, corrosion, dimensional changes, and thermally induced stresses that promote cyclic fatigue. These data will be extrapolated to longer use times to estimate lifetimes of the gas generator components. Methods will also be developed for preventing particulate plugging of the small platelet holes, which can affect complete mixing of fuel and oxygen inputs and lead to temperature gradients and hot spots in the combustion chamber. In addition, the testing capabilities of the High Temperature Materials Laboratory at Oak Ridge National Laboratory will be employed to analyze the gas generator's thermal barrier coating corrosion rates at elevated temperatures.

6.4 Turbines

Three turbine stages (high, intermediate, and low pressure) will be employed, with commercially available turbine technology installed in the Phase I system. For maximum research flexibility, individual turbines will be removable and replaceable with upgraded designs, as they become available. To facilitate future turbine replacement, each of the three turbines will drive a separate generator (see Figure12). Thermal power input to the turbines will be approximately 25 MW with an initial overall plant

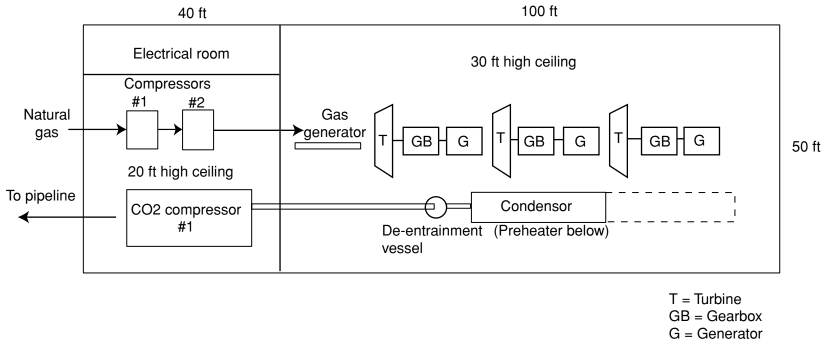


Figure 12. ZEST turbines (T), generators (G), and condenser.

efficiency estimated at 35%.[10] This assumes the use of a derated Solar gas turbine as an intermediate turbine stage. Using LLNL's multipole Halbach array generators, which were developed for advanced flywheel applications, it may be possible to eliminate the gearboxes between turbines and generators. This has the potential for raising plant efficiency by 2%.

As illustrated in Figure13, a reheater following the high-pressure turbine will raise the working fluid temperature to 2,200° F. Heat exchangers following the intermediate- and low-pressure turbines will preheat gas generator feedwater to approximately 600° F.

Near-term improvements in turbine technology are expected to raise inlet temperatures of the high-pressure turbine from 1,050°F to over 1,500°F using Rocketdyne adaptations of space shuttle turbines and to boost plant efficiency as high as 50%. Longer-term turbine improvements from the Next Generation Turbine Program may be able to attain 2,500°F inlet temperatures and 60% efficiencies.

Initial operating conditions envisioned for turbine stages in the Phase I plant are:

• *High-pressure turbine*
Inlet pressure 1,200 psi (8.3 MPa)
Inlet temperature 1,050 °F (57 °C)

• *Intermediate-pressure turbine*
Inlet pressure 140 psi (0.97 MPa)
Inlet temperature 2,200 °F (1,200°C)

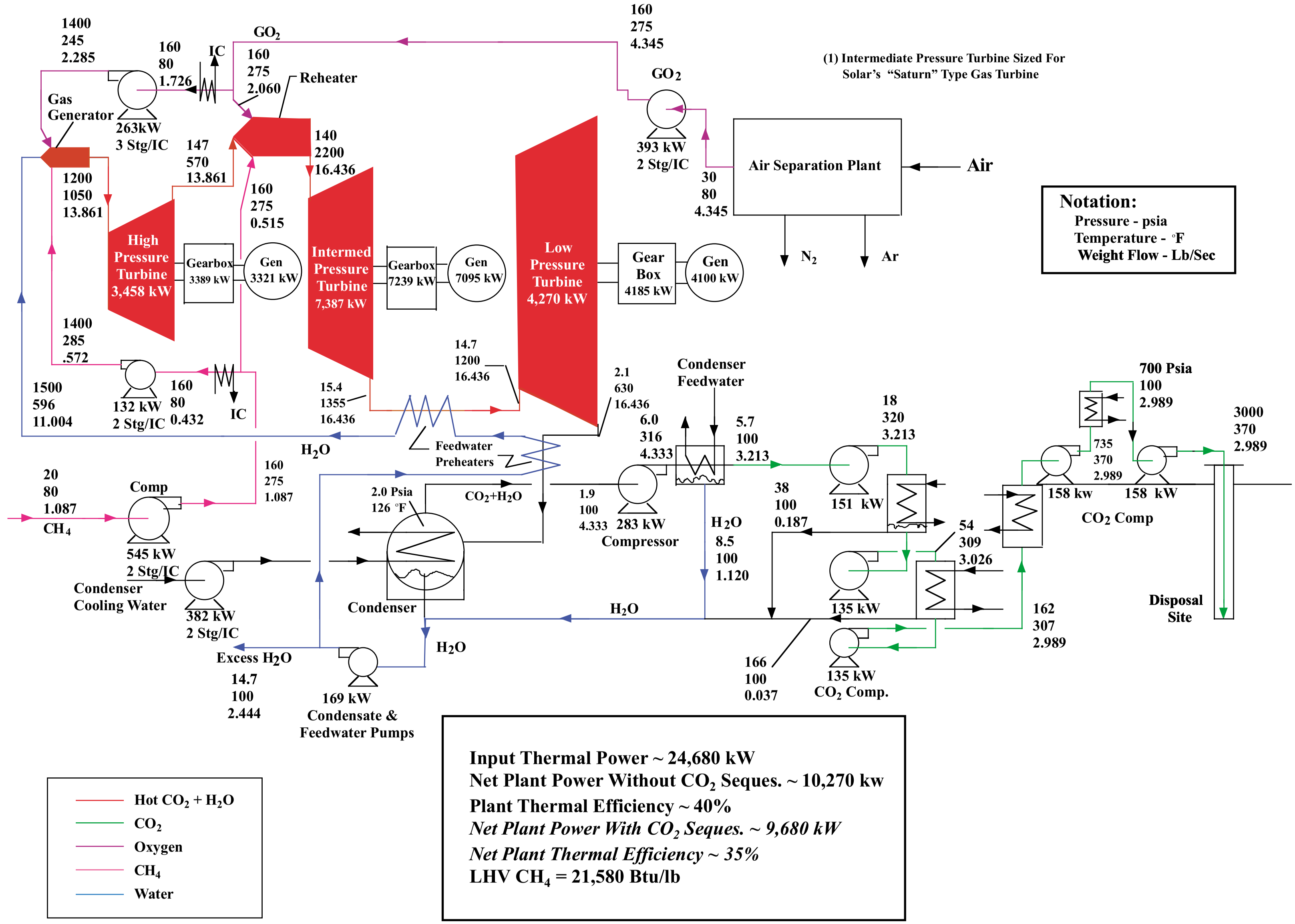
• *Low-pressure turbine*
Inlet pressure 14.7 psi (0.10 MPa)
Inlet temperature 1,200°F (650 °C)

[10] This efficiency estimate includes the power expenditure necessary for CO_2 sequestration. Without sequestration, the estimated efficiency is 38%.

Figure 13

LLNL 10 MW Zero Emissions Power Plant

(*Near Term Steam / Gas Turbine*[1] *Technology*)



Input Thermal Power ~ 24,680 kW
Net Plant Power Without CO_2 Seques. ~ 10,270 kw
Plant Thermal Efficiency ~ 40%
Net Plant Power With CO_2 Seques. ~ 9,680 kW
Net Plant Thermal Efficiency ~ 35%
LHV CH_4 = 21,580 Btu/lb

Exhaust from the turbines will consist mainly of steam (approximately 90% by volume) and CO_2 (10% by volume). Trace amounts of nitrogen and argon will also be present in quantities, depending on the purity of the input gases.

6.5 Condenser

Because of the presence of a high percentage of CO_2 in the exhaust, the condenser needs to be designed differently than for a conventional steam power plant. A larger heat transfer surface area will be required. The condenser will operate at a pressure of 2.0 psi and a temperature of 126°F. The small amount of dissolved CO_2 and SO_2 (generated from natural gas odorants) in the condensate will render it mildly acidic. Condenser materials, as well as all downstream materials used for condensate service, must be resistant to the expected acidity. This part of the power plant will thus need to be constructed of materials that are more corrosion-resistant than for conventional steam power plants. Suitable materials include aluminum alloys, titanium, many stainless steels, and other corrosion-resistant alloys such as Chloromet 2 and 3, Durco, Durichlor, Durcomet 100, Durimet 20, Duriron, Hastelloy, and Stellite. Besides being more resistant to the acidic concentrate, such materials will also limit the quantity of corrosion products entering the condensate.

6.6 Water Treatment

Potable industrial service-water will be used for startup, after purification through a 10-micron filter, an anion resin bed, a cation/anion mixed bed, and a 5-micron filter to assure a resistivity of one megohm or better. (Alternatively, the ZEST facility could utilize LLNL's sitewide low-conductivity water system to reduce capital cost.)

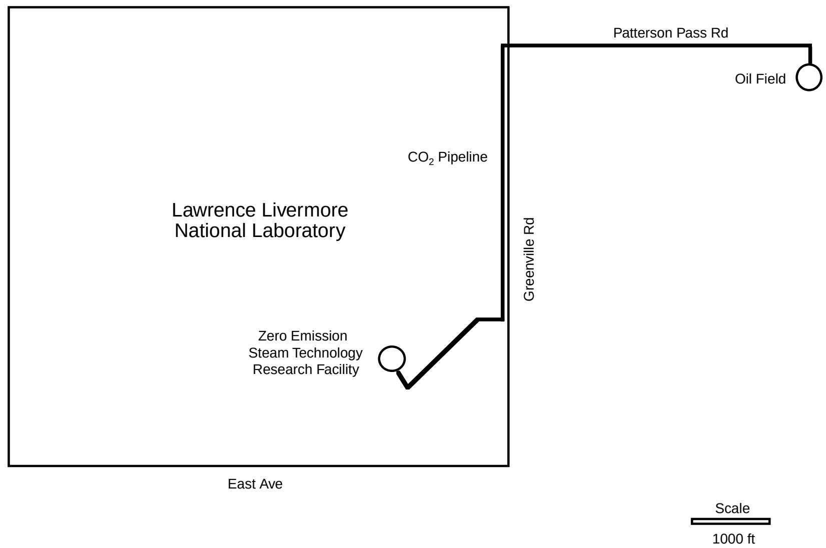
Because combustion of natural gas and oxygen generates water as one of the reaction products, the power plant will be a producer of water. A bleed stream will continuously remove excess water from the process and by so doing will provide a control on impurities buildup. This excess water will be used to reduce the amount of cooling water needed by the cooling tower.

Water impurities are expected to include approximately 400 ppm CO_2, 27 ppm SO_2, less than 1 ppm of other dissolved combustion products, and an unknown amount of dissolved corrosion products such as iron, nickel, and copper. While the bleed stream may be sufficient to maintain a level of water quality that still has to be determined, it may instead be necessary to treat the recycled water stream. Excess water leaving the plant may also have to treated. Its acidity could be neutralized, if needed, through various standard methods. One approach that might be particularly suited to the power plant would be to strip the dissolved CO_2 and SO_2 out of solution by sparging the bleed stream with nitrogen gas exiting the oxygen plant, or by passing the stream countercurrent to the nitrogen in a packed column. The stream could then be used as makeup water for the plant's cooling tower.

7. Carbon Dioxide Sequestration

Carbon dioxide from the ZEST facility will be transported by pipeline approximately one-half mile northeast of the plant, then injected—at the rate of 15,000 tons per year[11]—into two distinct geologic units. The first of these will be oil-bearing, either the Greenville sand (Cierbo formation) or a deeper marine facies (Tesla formation), which represent the primary and secondary pay zones of the Livermore Oil Field. The second unit will be an oil-barren saline aquifer that underlies the oil field (see Figures 14 and 15). Although the injection site lies east of LLNL, the Cierbo/Tesla formations and the underlying saline aquifer extend beneath the laboratory; monitoring wells can therefore be located either

Figure 14. Project location map.



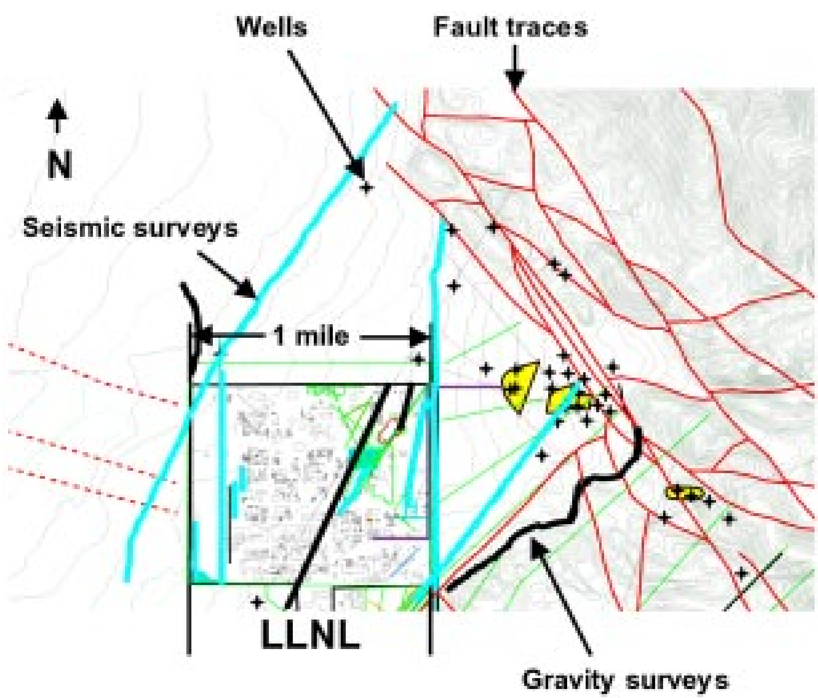


Figure 15. Field geophysical surveys provide extensive data on possible sequestration zones around LLNL. Wells that have been drilled are denoted by +'s. Oil-bearing zones are marked in yellow. Red lines indicate surface traces of faults. Blue and black lines denote locations of seismic and gravity surveys, respectively. Magnetic and resistivity studies have also been conducted in the area.

[11]Based on a plant size of 10 MW and a duty cycle of 50%.

within or beyond LLNL boundaries. The precise locations and sampling capabilities of such wells will be optimized for obtaining key geochemical and geophysical data.

Injection into the Livermore Oil Field exemplifies an often-used technique for enhanced oil recovery, where partial sequestration of CO_2 within the target formation represents an environmental benefit ancillary to economic gain. Injection into the deeper saline aquifer implements an often-*proposed* technique for isolating CO_2 waste streams from the atmosphere, where the direct benefit is environmental. This unique dual-injection approach permits simultaneous field assessment of CO_2 sequestration in both hydrocarbon reservoirs and oil-barren saline aquifers—the two primary formation types currently proposed for geologic sequestration.

7.1 Injection for Enhanced Oil Recovery

CO_2 floods for EOR are termed either "miscible" or "immiscible," depending on hydrocarbon density and pressure-temperature conditions within the target reservoir. Most common are miscible floods, which refer to implementations of the technique within reservoirs that contain light crude oil (API gravity of 28–45) at sufficient depth to define supercritical conditions for CO_2 (typically, greater than 2500 ft.). In these settings, the oil and CO_2 are highly miscible, which decreases viscosity (flow resistance) and increases specific volume (pressure) of the oil, thereby permitting additional production from otherwise inaccessible reserves. Immiscible floods refer to implementation of the technique within reservoirs that either contain heavy-crude oils (API gravity <20) or occur at insufficient depths to obtain supercritical conditions for CO_2 (typically, less than 2500 ft.). In such cases, extreme density contrast between the oil and CO_2 precludes significant miscibility of the two phases, which reduces effectiveness of the technique. However, improved production is still achieved, primarily by repressurizing the reservoir but also by limited viscosity reduction and swelling of the oil.

Of the 64 CO_2-flood projects ongoing in the United States as of March 2000, 63 are miscible floods, and 45 of these are in the Permian Basin of west Texas, owing to their relative proximity to large-scale natural CO_2 reserves in Colorado (McElmo Dome) and New Mexico (Bravo Dome).[12] The true cost of CO_2 extracted

[12] "2000 Worldwide EOR Survey." *Oil & Gas Journal*, March 20, 2000, p.45.

from such reserves is difficult to assess, although estimates of \$20/ton are common, with \$10/ton desirable. CES projections of the cost to sequester CO_2 generated by the ZEST facility, using commercially available steam-turbine technology in Phase I, is about \$17/ton of carbon (Figure 5). Assuming successful development of high-temperature turbine systems, this cost should drop to DOE's goal of \$10/ton.

Although EOR-related CO_2 injection has been used successfully by the petroleum industry since the 1970s, the *net* CO_2 *sequestration* obtained as a byproduct of this technique—that fraction of the injected fluid that remains in the target formation—has not been quantified precisely. DOE must evaluate this net sequestration to assess the potential role of EOR techniques in future U.S. carbon management. A fundamental goal of the integrated modeling work and field measurements associated with LLNL's proposed CO_2 flooding of the Livermore Oil Field is accurate characterization of the net sequestration achieved and the ultimate fate of this sequestered CO_2.

The Livermore Oil Field is located a half-mile east of LLNL within a seismically active, structurally complex region that marks the intersection of the Greenville and Las Positas fault zones. This small 50-acre field consists primarily of several distinct, structurally- and fault-trapped hydrocarbon accumulations at depths of 900–2000 feet within the 40–250-foot-thick Greenville sand of the Cierbo Formation. A minor secondary pay zone occurs at a depth of 5300 feet in the 35-foot-thick marine facies of the Tesla formation. The field was discovered and brought into production in 1967 and produced 1.42 million bbl of low-sulfur, 21–29 API gravity (light to intermediate crude) oil from 1967 to 1982; total expected production is 1.75–2.00 million bbl. Tertiary recovery via water flooding has now been carried out for some time. Current production, which is exclusively from the Greenville sand, is approximately 1000 bbl/month and has remained fairly constant since 1995.[13] Hence, this is a classic mature "stripper" field.

CO_2-flooding EOR in the Livermore Oil Field holds the potential to increase significantly this current stripper production rate. In addition, CO_2 flooding of oil accumulations in the Greenville sand offers an opportunity to investigate both the recovery effectiveness and the sequestration performance of an immiscible

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[13]Personal communication with Rick Jeeter, owner of oil leases for the Livermore Oil Field, 1 June 2001.

flood, while potential CO_2 injection into the deeper Tesla accumulation would permit such investigations of the more common miscible implementation. Although both possibilities will be pursued, the immiscible-flood scenario is especially intriguing because so little is known about this currently uncommon method. It is also particularly relevant to California, whose preponderance of shallow oil reserves—all of which represent potential immiscible-CO_2-flood targets—is well documented.[14] In this regard, it is worth noting that although uncommon and less efficient than their miscible counterparts, all seven of the ongoing immiscible floods worldwide have been rated "successful" or "promising."[15]

For either immiscible- or miscible-flood EOR, the CO_2 injection well will be equipped to facilitate tight control of well-head pressure, temperature, and injection rate. A strategically located series of monitoring wells will permit sampling of formation mineralogy and fluids; these wells will also be equipped with sensors to facilitate geophysical imaging of the CO_2 front as it migrates through the formation. These geochemical and geophysical data represent an invaluable means of benchmarking and improving computational modeling capabilities.

7.2 Injection for Environmental Isolation

Carbon dioxide injection into deep saline aquifers for the sole purpose of environmental isolation represents arguably the most attractive geologic alternative for large-scale sequestration. Statoil (Norway's state oil company) estimates that storage capacity within European saline aquifers, primarily those beneath the North Sea, exceeds 800 billion metric tons—a quantity greater than the total amount of CO_2 emitted to the atmosphere since preindustrial times. At the present rate of CO_2 generation by all the power stations in Europe, approximately one billion metric tons per year, the continent's saline-aquifer storage capacity would be sufficient to sequester all CO_2 generated for the next 800 years.[16]

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[14]Sally M. Benson, "Comparison of Three Options for Geologic Sequestration of CO_2: A Case Study for California," *Proceedings of 5th International Energy Agency's International Conference on Greenhouse Gas Control Technologies*, Cairns, Austrailia, August 2000.

[15]"2000 Worldwide EOR Survey." *Oil & Gas Journal*, March 20, 2000, p.45.

[16]Tore A. Torp, "Capture and Reinjection of CO_2 in a Saline Aquifer at Sleipner Field and the Future Potential of this Technology," *Dinner-debate with the fondation Europeenne de l'Energie in Brussels*, Statoil Research Centre, Trondheim, Norway, 2 June 1998.

U.S. sequestration options in terms of saline aquifiers are currently being quantified. The thick sedimentary basins of California's Central and Imperial Valleys, which range up to 8000 meters in depth, offer extensive storage possibilities. Estimated CO_2 sequestration capacity of Central Valley sediments alone exceeds 300 years of current California annual CO_2 emissions. Imperial Valley sediments add another 60 years of CO_2 emissions to this storage capacity. [17]

The key attributes of saline aquifers include their broad geographic distribution, their immense sequestration potential, and the demonstrated integrity of their confining cap-rock formations. However, because this pure-isolation approach yields—at present—no direct economic benefits to industrial concerns in most countries, there is only one field project in the world that has implemented the concept. This is the unique North-Sea Sleipner facility, owned and operated by Statoil, in which one million metric tons of CO_2 have been injected annually into a confined sandstone aquifer since 1996. Although certain Sleipner field data are obtainable from Statoil and their collaborators, the most critical samples and measurements either have not been taken or are—at present—proprietary and therefore unavailable. Hence, U.S. scientists currently lack access to the most important field data associated with CO_2 injection into saline aquifers, even though DOE recognizes this as one of its most promising long-term sequestration options.

In contrast to the situation for EOR, CO_2 is largely *immiscible* with the saline formation waters it typically encounters within deep confined aquifers. Because it is also considerably less dense than these ambient saline fluids, most of the injected CO_2 will rise toward the aquifer cap rock as an immiscible plume, which then migrates laterally beneath this permeability barrier. The plume/formation-water interface is typically irregular, owing to the lower viscosity of CO_2, which leads to "viscous fingering" of the plume within regions of heterogeneous permeability.

As the injected CO_2 migrates via these processes of immiscible displacement, gravity segregation, and viscous fingering, fractions of it will be "trapped" by each of three fundamental sequestration processes:

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[17] Sally M. Benson, "Comparison of Three Options for Geologic Sequestration of CO_2: A Case Study for California," *Proceedings of 5th International Energy Agency's International Conference on Greenhouse Gas Control Technologies*, Cairns, Austrailia, August 2000.

- Mineral trapping, or reaction with formation minerals to precipitate carbonates.
- Solubility trapping, or dissolution into formation waters.
- Hydrodynamic trapping, or isolation beneath the cap rock within localized structural highs of the aquifer.

Scientific viability of geologic sequestration within saline aquifers hinges on the relative effectiveness of these migration and sequestration processes, while its successful implementation relies on our ability to predict sensitivity of this migration/sequestration balance to key physical and chemical characteristics of potential target reservoirs. Quantification of this sensitivity reveals geochemical, hydrologic, and structural constraints on maximizing sequestration performance that can be used to identify those formations most likely to provide optimal storage capacity and isolation security. At LLNL, we have integrated a state-of-the-art reactive-transport simulator (NUFT), comprehensive supporting geochemical software and thermodynamic/kinetic databases (SUPCRT92, GEMBOCHS), and recent equation-of-state and viscosity formulations for CO_2 to develop a unique modeling capability for identifying optimal target formations for CO_2 sequestration.

Confidence in this modeling approach necessarily follows from success in simulating the observed behavior of field systems. Hence, our initial studies have focused on simulating CO_2 injection at Sleipner and quantifying the relative effectiveness of structural, solubility, and mineral trapping in Sleipner-like settings.[18] Although this work provides first-of-its-kind quantitative insight into these interrelated sequestration processes, the skeletal nature of Sleipner field observations—which are needed to evaluate and constrain model predictions—spotlights the importance of obtaining a complete set of such observations from a well-characterized field project in the United States. Hence, the saline-aquifer disposal component of ZEST will fill a critically important need.

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[18] Johnson, J.W.; Nitao, J.J.; Steefel, C.I.; and Knauss, K.G., 2001, "Reactive transport modeling of geologic CO_2 sequestration in saline aquifers: the influence of intra-aquifer shales and the relative effectiveness of structural, solubility, and mineral trapping during prograde and retrograde sequestration." *Proceedings of the First National Conference on Carbon Sequestration,* May 14-17, 2001. <http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/P28.pdf>

The same injection and monitoring wells described above for the EOR project will be employed in this deeper saline-aquifier project, although wellhead pressure at the injection well will be increased appropriately. This cost-saving dual usage is made possible by outfitting each of the wells with a down-hole string of packing devices that permit collection of geochemical and geophysical data from isolated vertical sections. These data will be used to quantify the relative contributions of mineral and solubility trapping and to delineate the magnitude, migration path, and time-dependent location of the immiscible CO_2 plume. Each of these parameters represents a critical constraint on our computational simulation capabilities.

Figure16 depicts a dual-injection approach to CO_2 storage in the formations adjacent to LLNL.

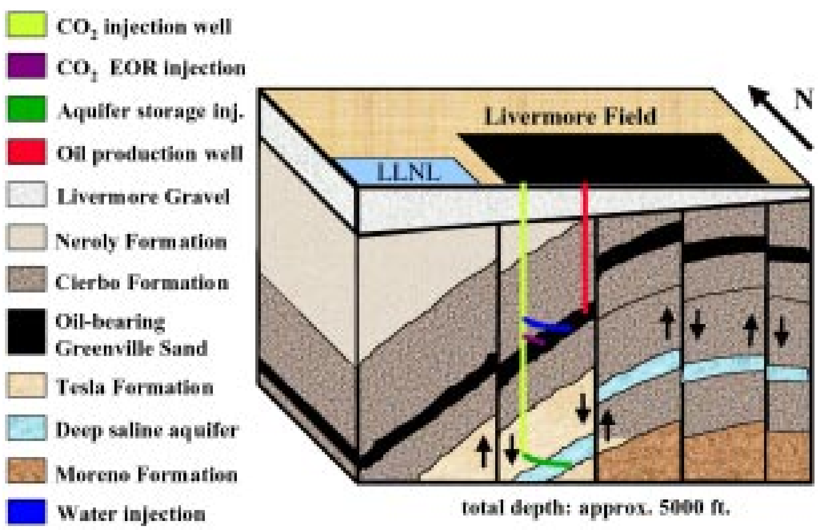

Figure 16. Dual-injection approach to CO_2 sequestration: Enhanced oil recovery and saline aquifer storage.

At present, regulations covering CO_2 sequestration in saline aquifiers do notexist. Injecting CO_2 into an oil-barren underground formation is a new concept, and the regulatory process has not yet addressed this issue. Although pure CO_2 is not a hazardous substance, impurities within a CO_2 waste stream may be hazardous. The large quantities of high-pressure CO_2 being injected into saline aquifers may also have unforeseen consequences that create the need for regulation. During the ZEST project, LLNL will seek to generate critical data that regulators can use to formulate appropriate sequestration regulations. In particular, ZEST sequestration studies will attempt to identify the environmental and human health risks associated with CO_2 injection into saline aquifers and to determine threshold impurity concentrations in the stream that can lead to harmful impacts.

8. Why LLNL Is the Best Site for This Project

A combination of factors points to LLNL as the logical host for ZEST. LLNL has unique site attributes that include proximity to petroleum and groundwater basins of the right depth, size, and maturity to serve as ideal field laboratories for geologic sequestration. In addition, LLNL staff have expertise in several areas that are key for successful development of ZEST, including:

- Ceramic membrane oxygen separation.
- Thermal barrier coating technology for high-temperature turbines and gas generator.
- Computational capabilities: turbulent combustion simulation.
- Computational modeling capabilities: Geologic CO_2 sequestration.
- Geophysical imaging and geochemical sampling and analytic capabilities.
- Carbon dioxide injection and enhanced oil recovery in seismically active oil basins.

It is well known that local opposition to power-plant sitings on the basis of perceived health and quality-of-life issues can be very difficult to overcome, especially in California. This holds true even for small facilities such as ZEST. Stakeholder opposition to new plants, however, generally focuses on the risks from toxic air emissions, and the zero-emissions aspect of this proposed plant is expected to help greatly in winning local support. ZEST will be presented to the local community as an environmentally friendly alternative to traditional electric power plant technologies, which present severe air quality and global warming issues.

8.1 Ceramic Membrane Oxygen Separation

LLNL has successfully fabricated high-performance oxygen gas separation membranes. Our supported thin-film membranes are processed using a proprietary low-cost manufacturing technique that employs only inexpensive materials and no precious metals. We have measured oxygen fluxes through our membranes of up to 15 sccm (standard cubic centimeters per minute) at 1650˚F (900˚C) in air/methane gas mixtures, an improvement of 30% over state-of-the-art competitive technologies under the same conditions. In addition, we have developed a precisely controlled, low-cost colloidal spray technology for dense ceramic layer manufacture for our solid oxide fuel cell program that is also suitable for oxygen separation membrane production (see Figures 17 and 18).

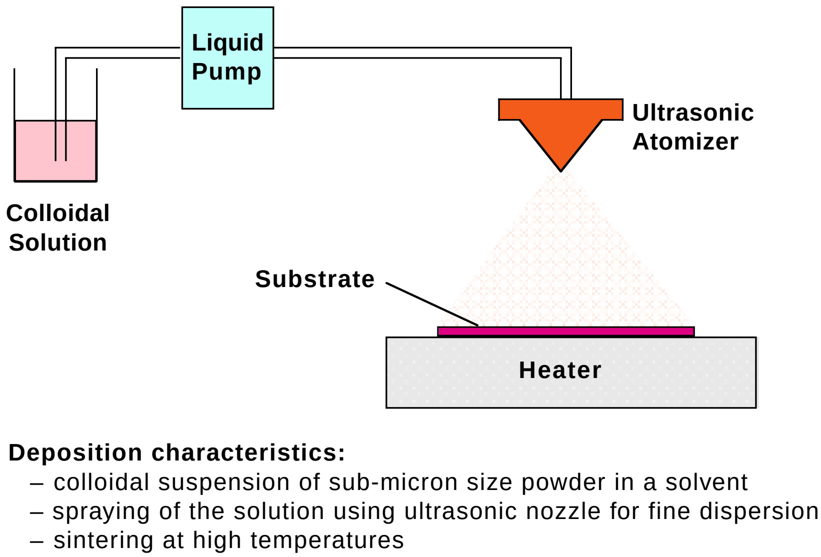

Figure 17. LLNL's colloidal spray deposition techniques can produce dense ceramic layers suitable for oxygen separation applications.

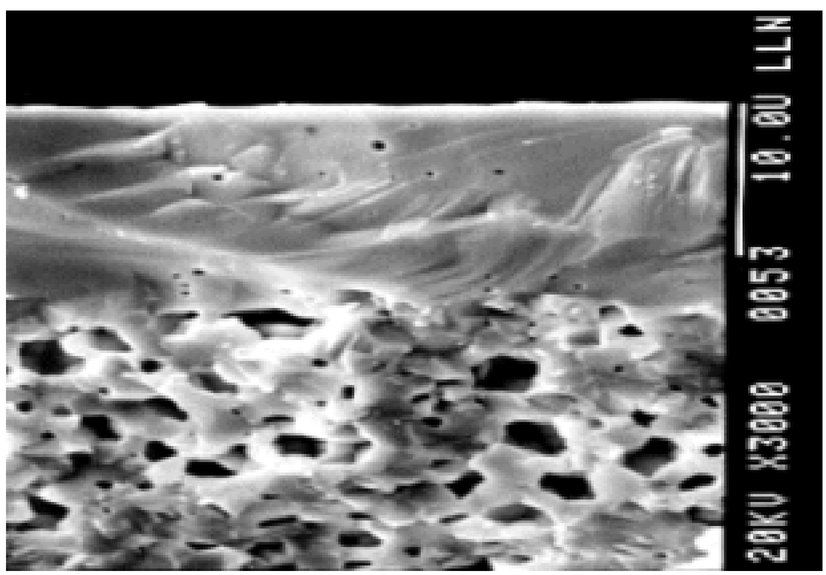

Figure 18. Scanning electron microscope image of a fully dense ceramic layer deposited on substrate using LLNL's colloidal spray deposition technology.

8.2 Thermal Barrier Coating Technology for High-Temperature Turbines and Gas Generator

LLNL has a history of developing proprietary thermal barrier coatings for industrial turbine companies, under CRADA agreements. We have successfully fabricated microstructure layers of yttrium/zirconium alloys alternating with alumina for use as turbine airfoil thermal barrier coatings, with deposition control at near-atomic levels (Figure19). A scanning electron microscope image of a 50-µm-thick yttria-stabilized zirconia electron-beam deposit applicable to turbine-blade coatings is depicted in Figure 20. Many of our deposition techniques were developed during our design and fabrication of x-ray mirrors for defense-related lasers technology. Our specialty coatings have also been used in developing compatible materials for uranium separation processes and solid-oxide fuel cell manufacture. In addition, LLNL has a wider range of characterization tools for analyzing the coatings than can be found at most other research facilities.

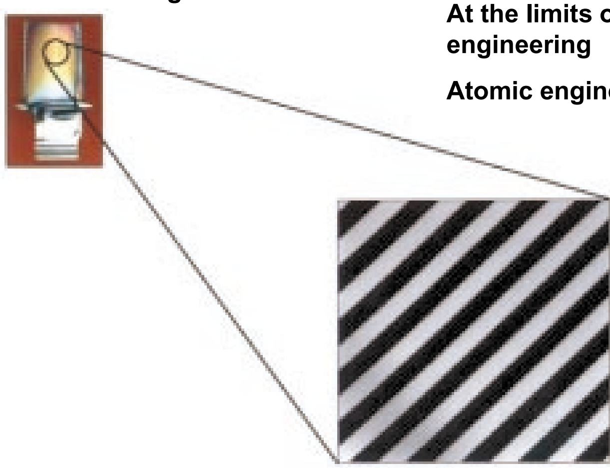

Figure 19. Thermal barrier coatings are achievable with control at near-atomic levels.

8.3 Computational Capabilities: Gas Generator Combustion Region

LLNL has developed a sophisticated multiphysics code entitled the Arbitrary Lagrangian and Eulerian Three Dimensional (ALE3D) code that combines computational fluid dynamics, structural mechanics, heat transfer, and reaction chemistry. It is capable of modeling both the reaction chemistry and the acoustic wave environment of the gas generator's combustion region, including shock wave formation and propagation. Understanding these parameters is critical for combustion stability analysis.

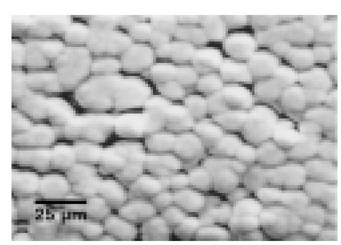

Figure 20. Electron microscopy image of electron-beam-deposited yttria-stabilized zirconia suitable for turbine-blade coatings.

Detailed chemical kinetics simulation methods have also been developed at LLNL and are used by research teams around the world. These codes will be especially important in tracking minor species through ZEST's combustion process. An important area of research and development in the ZEST project is to combine LLNL's chemical kinetics simulation capabilities with its

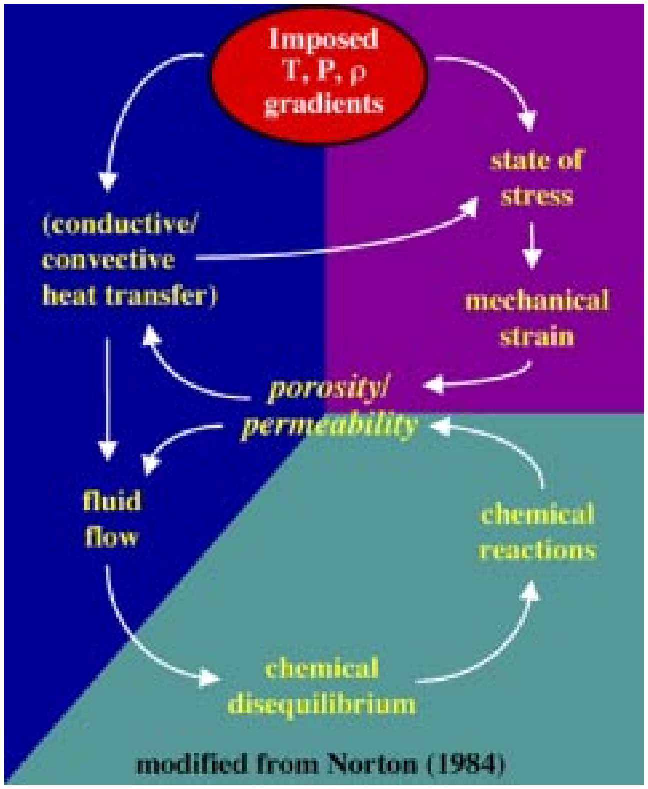

Figure 21. Reactive transport modeling: an advanced simulation capability for geologic systems. Coupled processes can be represented that redistribute mass and energy within geologic systems to resolve disequilibrium temperature, pressure, and fluid-density gradients imposed by natural or engineered perturbations. (Modified from D. Norton, 1984, "Theory of Hydrothermal Systems," Annual Review of Earth and Planetary Sciences, v. 12, pp. 155-177.)

ALE3D fluid dynamics software, to develop an extremely powerful multiphysics code capable of modeling many different combustion environments. This combined code will be utilized by NETL with the Pittsburgh Computing Center's teraflop parallel-processor computer. Eventually this code is expected to become a tool used by the gas turbine industry.

An accurate simulation of the entire combustion and power generation process, and of the effect of feedback flows on combustion, is essential to optimize ZEST's performance and to understand how to build in a fail-safe control system that will allow reliable, safe operation of the system. The process simulations will be the basis for developing a control strategy for plant operations and, in particular, for designing high-speed controls for the combustor.

Another application for our simulation tools is to understand the load-following capabilities of ZEST. An area of research will be to maximize the turn-down ratio of the ZEST plant, with a goal of attaining a 2-to-1 difference between peak and minimum electrical output. Our computational capability will allow us to precisely model the system to maximize turn-down ratio, implementing the design into ZEST's actual combustion operations.

8.4 Computational Modeling Capabilities: Geologic Carbon Dioxide Sequestration

Carbon sequestration science represents an emerging core capability of LLNL's Energy and Environment Directorate, with more than \$3M in FY01 internal and external support across nearly 20 projects. In particular, scientists in this directorate have developed an internationally recognized suite of kinetically-controlled reactive-transport and multiphase-flow simulators (GIMRT, NUFT), supporting geochemical software (SUPCRT92, JEWEL), and thermodynamic/kinetic databases (GEMBOCHS). This integrated computational toolbox provides a unique modeling capability for representing coupled thermal, hydrologic, geochemical, and mechanical processes in complex subsurface environments (see Figure 21).

An ongoing (FY00–FY01), internally funded project has focused on customization of this capability to identify and address key technical issues associated with geologic sequestration of CO_2 waste streams. Beyond implementing the requisite model modifications and additions, the project team has established a collaboration with Statoil, which resulted in access to sufficient field data from their Sleipner project to permit reactive-transport simulations of this unique geologic sequestration site as an initial test case.[19] In addition, LLNL scientists are presently carrying out modeling work in the DOE/NETL-sponsored geologic sequestration program, which aspires to "deliver the technology and information needed to enable application of safe and cost-effective methods for geologic sequestration of carbon dioxide by the year 2015."

In view of our recent model advances, application experience, and international collaborations directly focused on geologic CO_2 sequestration, LLNL is ideally poised—from a computational simulation perspective—to fully exploit the wealth of field data that will be collected at the ZEST field-sequestration facilities.

8.5 Geophysical Imaging and Geochemical Sampling and Analytic Capabilities

LLNL's leading-edge computational modeling tools for addressing geologic sequestration issues are complemented by a wide range of advanced geophysical imaging/interpretation and geochemical sampling/analytic capabilities. Geophysical capabilities include both seismic and electrical methods. Seismic reflection and transmission imaging (SRI and STI) techniques permit subsurface 3-D mapping of lithologic boundaries; electrical resistance tomography (ERT) imaging provides critical informa-

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[19] Johnson, J.W.; Nitao, J.J.; Steefel, C.I.; and Knauss, K.G.; 2001. "Reactive transport modeling of geologic CO_2 sequestration in saline aquifers: the influence of intra-aquifer shales and the relative effectiveness of structural, solubility, and mineral trapping during prograde and retrograde sequestration." *Proceedings of the First National Conference on Carbon Sequestration,* May 14-17, 2001. <http://www.netl.doe.gov/publications/proceedings/01/carbon_seq/P28.pdf>

tion regarding the properties of subsurface fluids. These imaging techniques, together with associated interpretive methodologies, will be used to define the precise geometry of target formations for both EOR and pure-isolation targets, as well as the migration paths of injected CO_2.

Geochemical sampling and analytic techniques will be used to determine pre- and post-injection mineralogy, as well as aqueous-fluid and hydrocarbon compositions. Cores and fluid samples from the monitoring wells (including post-injection side-wall cores) will be collected and analyzed using a variety of techniques. Detailed mineralogy will be determined using techniques that include:

- Standard petrographic analyses.
- Electron microprobe techniques.
- Scanning electron microscopy (SEM).
- Transition electron microscopy (TEM).
- X-ray diffraction (XRD).

Fluid inclusion analysis of secondary carbonates will be used to determine the precise composition and temperature of precipitating fluids. Several techniques will be employed to determine bulk composition of sampled formation waters:

- Light cation concentrations will be derived from inductively-coupled plasma atomic emission spectroscopy (ICP-AES).
- Heavy cation concentrations will be obtained from inductively-coupled plasma mass spectroscopy (ICP-MS).
- Anion concentrations will be obtained from liquid chromatography (LC).

These determinations may be supplemented by in-situ fiber-optic analysis of data collected remotely from down-hole optrodes. Hydrocarbon compositions will be determined using gas chromatography (GC), mass spectroscopy (MS), and total carbon analysis.

8.6 Carbon Dioxide Injection and Enhanced Oil Recovery in Seismically Active Oil Basins

LLNL has a strong capability in the design of enhanced oil recovery systems, as well as in the modeling of seismic effects. We are currently imaging CO_2 and water injection for the Chevron Lost Hills oil field in California's Central Valley, employing 2-kHz electromagnetic transmission imaging as well as electrical resistivity imaging that is able to resolve geological features as small as 10 feet. These data are being collected down-hole, largely in the 1600-to-1700-foot-depth region, approximately the same depth as the oil deposits in Livermore's Greenville formation, where the CO_2 from ZEST will be sequestered (see Figures 22 and 23).

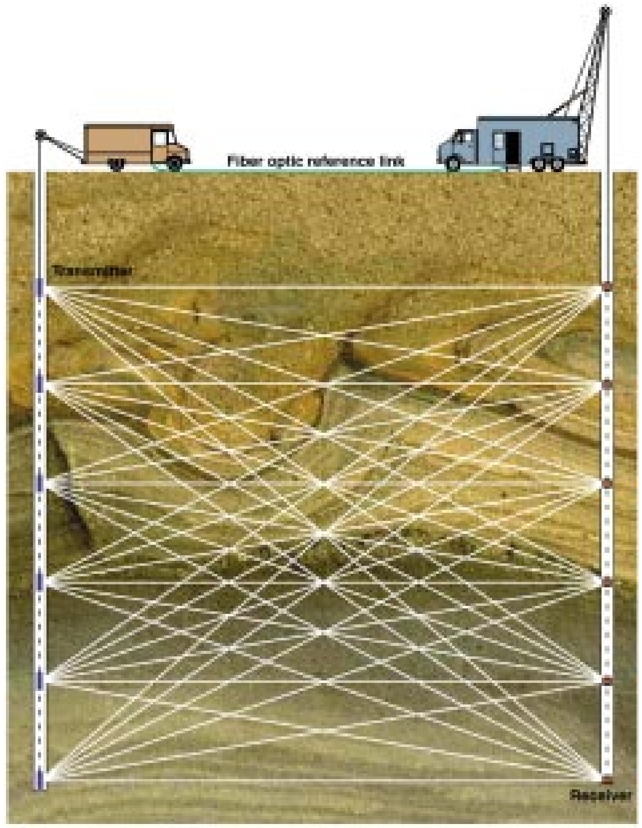


Figure 22. Cross-well electromagnetic imaging of CO_2 and water injection.

In our partnerships with the DeepLook Consortium and NETL, we have developed petroleum basin simulation codes with state-of-the-art transport and kinetics features. In projects with the Gas Research Institute (GRI), NETL, and its National Petroleum Technology Office (NPTO), we have fabricated tiltmeter instrumentation with nanoradian sensitivity that can fit within a 2.5-inch-diameter well bore, in order to map reservoir

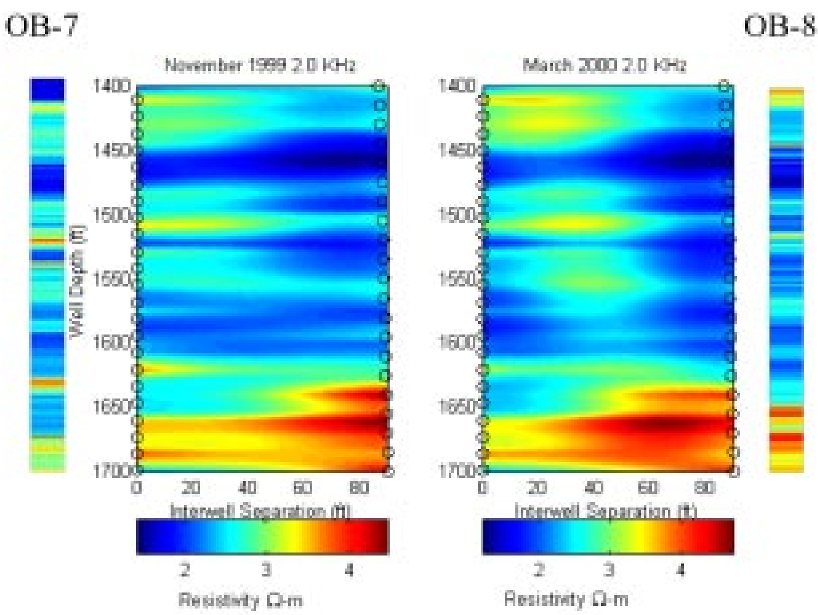


Figure 23. Two-kilohertz cross-well electromagnetic imaging for use in secondary enhanced oil recovery operations.

Figure 24. LLNL tiltmeters with nanoradian sensitivity can fit within a 2.5-inch-diameter well bore and can map reservoir pressure and basin reinflation. The tiltmeter has a 110° autogimbled range.

pressure and basin reinflation (Figure 24). We also have performed advanced perforation technology studies in partnership with NETL, using sequential shaped-charge penetration methods.

Novel noble gas tracers (such as krypton isotope formulations) have been developed at LLNL that can be used to spike injected carbon dioxide. Other areas of specialty include the chemical kinetics of water/rock/CO_2 interactions; gas-phase vadose zone transport; and geochemical modeling.

9. Competitive Technologies

Technologies that have some of the same advantages as ZEST, and that may in the future compete for the same market niche, include:

- Combined-cycle turbines.
- Solid-oxide fuel cells.
- Coal syngas generation combined with fuel cells.

9.1 Combined-Cycle Gas and Steam Turbines

A combined Brayton-cycle gas turbine and Rankine-cycle steam turbine is typified by high efficiencies but includes inherent energy losses of approximately 15% in the heat exchanger energy coupling between combustion gas and steam units. A ZEST plant, which will rely on an internal Rankine cycle, is not limited by coupling losses and may be able to attain efficiencies of >60% for the same turbine inlet temperatures.

Combined-cycle plants generate oxides of nitrogen and CO_2 emissions. Although the CO_2 can be separated and sequestered, estimated costs run $72 to $110 per ton of carbon. ZEST plants, which will burn pure oxygen instead of air, will generate no oxides of nitrogen. All CO_2 emissions will be sequestered at an estimated cost of only $10 to $17 per ton of carbon. (See Figure 5.)

9.2 Solid-Oxide Fuel Cells

Siemens-Westinghouse is developing a zero-emission plant design that employs solid-oxide fuel cells and ceramic oxygen transport membranes. At present, the capital costs for this technology are very high—perhaps $10,000 per kilowatt. To date, the biggest demonstration plant is smaller than 1 MW. Although there is much promise for this technology in the future, the potential to scale the design to higher powers has not yet been demonstrated.

9.3 Los Alamos National Laboratory (LANL) Zero Emission Coal Power Plant

LANL's zero emission coal (ZEC) concept involves hydrogen generation from coal, use of the hydrogen in a high-temperature solid oxide fuel cell, and binding the CO_2 as a mineral through carbonation of magnesium silicates. LANL states that there will be no CO_2, SOx, NOx, particulates, or mercury produced. LANL has put together a team composed of major utilities, coal and energy companies, and government entities and hopes to build a pilot process plant. It is anticipated that this technology will mature after the ZEST technology has matured. Very large quantities of solid material must be transported to sequester the CO_2 as carbonates, and these transportation costs may limit the economic viability of the ZEC concept.

10. Facility Design, Engineering Services, and Construction Plan

ZEST facility design, engineering services, and other related project functions will be performed by a combination of architectural and engineering (AE) firms and LLNL's Plant Engineering organization. Construction and procurement will be accomplished through the use of fixed, competitively-bid contracts and subcontracts. Activation of the research facility will be accomplished by LLNL staff.

10.1 Project Participants

LLNL Design and Engineering Services

LLNL will develop project-specific design criteria, perform value engineering, and carry out selection of the AE firm. LLNL will also provide engineering services during Title III and will support and monitor the selected AE firm during Title I, II, and III services.

LLNL Construction Services

LLNL will contract for construction and provide construction services for the project as agreed by the Federal Project Manager and the LLNL Project Manager.

Long-Lead Components

- Components for cryogenic oxygen separation plant.
- Gas generator.
- High-, intermediate-, and low-pressure turbines.
- Electrical generators.
- Reheater(s).
- Condenser.
- Carbon dioxide compressors.

10.2 Facility Construction Budget Estimate

The facility budget estimate is detailed in Appendix B, which consists of a Preliminary Design Study and Cost Estimate for Zero Emission Steam Technology Research Facility, prepared by Bechtel National Inc. and submitted to LLNL on June 30, 2000. This study includes cost estimates for all components of the ZEST plant except for a demonstration ceramic membrane oxygen separation plant. The estimate for the demonstration plant was prepared by Praxair.

Note: Bechtel calculated all capital cost estimates, except for the ceramic membrane oxygen plant, which was calculated by Praxair. Operating costs include personnel, fuel, and water treatment expenses. The approximate 10-MW size of the ZEST research facility was chosen as a compromise between a larger facility (for greater credibility in scaling to 50-MW to 100-MW sizes) and a smaller facility (to minimize operating costs).

The major ZEST construction budget items and estimated costs are listed in Table 1.

Table 1. ZEST Facility Construction Budget Summary
(3Q FY01 $ Million)

	Cost	Contingency	Total
Engineering	5.6	2.0	7.6
Plant facility			
Process equipment and cryogenic oxygen plant	27.6	9.7	37.3
Ceramic membrane oxygen plant	1.4	0.5	1.9
Process facilities	2.7	0.9	3.6
Support facilities	1.3	0.5	1.8
LLNL site preparation and tie-in	4.8	1.7	6.5
Plant facilities total	37.9	13.2	51.1
Pipeline and well systems			
Carbon dioxide pipline	2.0	0.7	2.8
Injection well system	2.1	0.8	2.9
Oil field facilities	0.8	0.3	1.1
Pipeline and well total	5.0	1.8	6.8
Total capital cost	48.5	17.0	65.5
Annual operating cost	1.5		1.5

Note: Based on preliminary Bechtel study of Spring 2000. Costs include project engineering, management, and integration. Costs do not include DOE management.

10.3 Proposed Funding Schedule and Milestones

Funding to design and construct the ZEST research facility will span six years. Based on the preliminary Bechtel costing study, a breakdown of the funding proposed during each of these years—and the milestones to be met—is included in Table 2. Note that the Table 2 estimate differs slightly from Table 1 because this cost estimate includes escalation to mid-construction and realistic project management costs.

All ZEST design and construction activities will be carried out according to DOE's critical design process, as required under DOE Order 413.3. This process will ensure that the required mile-

Table 2. Proposed Funding Schedule and Milestones (3Q FY01 $ Million)

Activity	Duration Months	Total	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
MILESTONES								
Critical Decision Points			CD-0	CD-1		CD-2	CD-3	CD-4
Select A/E Contractor								
Authorize Construction								
Select Facility Contractor								
Select Oil Field Contractor								
End of Construction								
Operation Reviews								
Start-up & Operations								
PROJECT MANAGEMENT								
Project Definition	10							
DOE Action	9							
Contractor Evaluation	6							
Permitting & Licensing	36							
DESIGN/ENGINEERING								
Conceptual Design	9							
Oil Field Baseline Investigation	3							
Preliminary Design (Title I)	6							
Detailed Design (Title II)	12							
Construction Support (Title III)	21							
PROCUREMENT								
Procurement	27							
CONSTRUCTION								
Power Plant Facility	21							
Pipeline and Injection Well Systems	15							
COST								
Total Estimated Cost (TEC)		(3Q FY01 $Million)						
Design & Engineering (note 1)		7.6			3.0	3.0	0.9	0.7
Project Management (note 2)		4.1			0.7	1.0	1.5	0.9
Construction Management		4.7			0.2	1.1	2.5	0.9
Construction (note 3)		48.9			3.1	15.1	25.0	5.7
Subtotal TEC		65.4			7.0	20.2	29.9	8.2
Other Project Costs (OPC)		(3Q FY01 $Million)						
Conceptual Design		0.6	0.2	0.2	0.2			
Hazards Analysis, NEPA (EA), & Permits		0.3		0.2	0.1			
Risk Reduction Engineering		3.0		1.0	2.0			
Misc. Other Costs (note 4)		0.9		0.5	0.4			
Subtotal OPC		4.8	0.2	1.9	2.7			
Total Project Cost (TPC)		70.2	0.2	1.9	9.7	20.2	29.9	8.2
			Year 1	Year 2	Year 3	Year 4	Year 5	

1. Also includes LLNL project engineering and management.
2. Includes project integration, but does not include DOE management cost.
3. Assumes early funding for procurement of long lead items (turbine system and combustor).
4. Includes early oil field baseline investigation.

stones for construction are met. The appropriate timing of critical decision processes is included in Table 2.

10.4 Industrial Partner Share-of-Cost

LLNL is placing a high priority on obtaining an industry share-of-cost for the ZEST project of at least 20%, to be acquired as early in the project as possible. An industrial stakeholders workshop in August 2001 is a forum for seeking industrial comment on facility design and operation and exploring options for the management and operation of the research facility.

11. ZEST Research and Operations Management Plan

11.1 Organizational Structure

LLNL's ZEST Research Facility Manager will report to the associate director of LLNL's Energy and Environment Directorate, who in turn reports to the Director of LLNL. (See the organization chart in Figure 25). The ZEST Manager will oversee both research and development activities and engineering and maintenance functions of the facility. The ZEST Manager will receive guidance from key DOE personnel, who include the Deputy Assistant Secretary for Coal and Power Systems, and the NETL Associate Director of the Strategic Center for Natural Gas. In addition, to make ZEST's research agenda responsive to the needs of U.S. industry, an Industrial Advisory Panel will be formed that will be composed of technical experts from the U.S. electric power generation and oil and gas industries. Each year, the ZEST Manager, working closely with the Industrial Advisory Board and DOE oversight personnel, will draft a research plan for the ZEST facility that sets research priorities for the coming year and includes a proposed facility budget for R&D activities and engineering and maintenance operations.

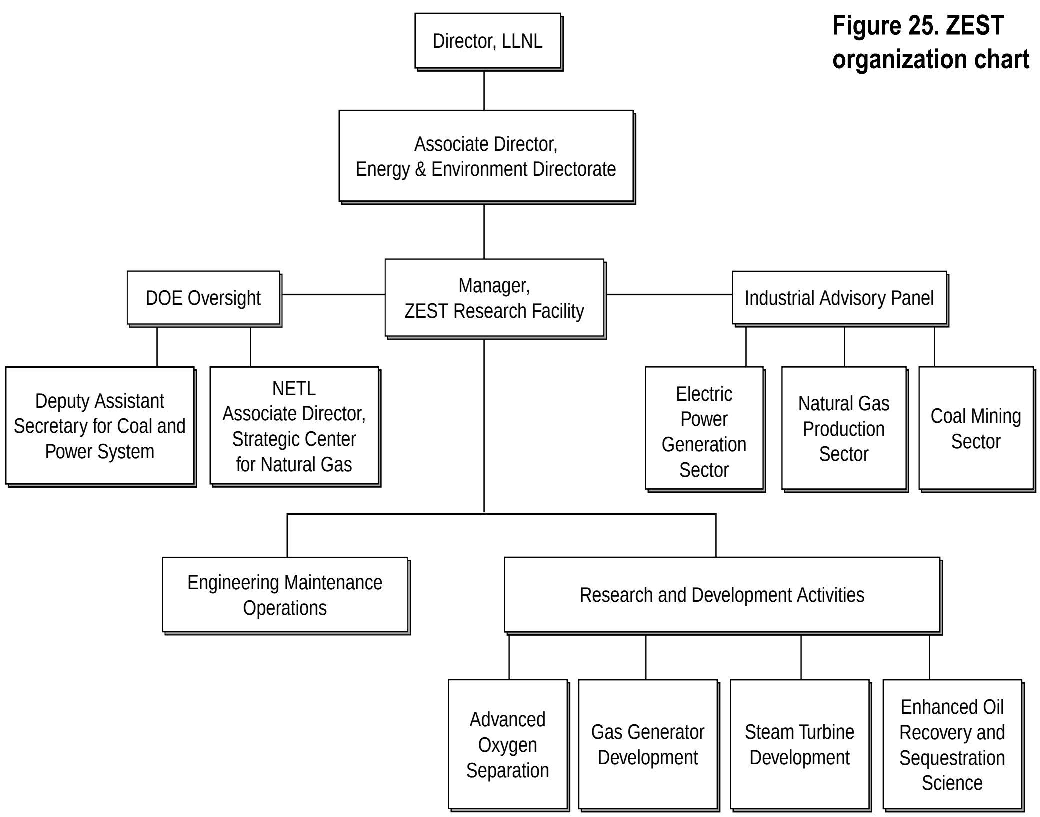


Figure 25. ZEST organization chart

11.2 Annual Research Activities

Critical research activities will include development of novel technologies and improvement of existing technologies key to the success of ZEST. Each year, the ZEST Manager will detail and develop the research projects and budgets that can best meet ZEST's research goals and answer the specific questions necessary to speed ZEST's adoption by industry. One of the most important research goals will be to minimize the risks of critical equipment failure. LLNL envisions, for instance, that many research activities will focus on reducing the technical risk of gas generator failure. Other critical research will target development of ceramic oxygen separation membranes for the oxygen plant; thermal barrier coating and combustion modeling for the gas generator; using CO_2 to enhance oil recovery from shallow, mature fields; and CO_2 sequestration science for both oil-bearing and confined aquifer formations. An estimated FY05 budget for ZEST research and operations, including project management expenses, is included in Table 3.

Table 3. FY05 ZEST Research and Operations Budget Estimate

Activity	Budget ($M)
Gas generator development	1.00
Ceramic membrane oxygen separation development	0.75
Thermal barrier coating development	0.75
Combustion modeling	0.75
Enhanced oil recovery	0.35
CO2 sequestration analysis, tracking, and monitoring	0.75
Program management and administration costs	0.40
Research Budget Total	**4.75**
Operating Cost	**1.72**
TOTAL	**6.47**

Appendices

Preliminary ZEST research facility designs and cost estimates were prepared in FY00 by LLNL's Plant Engineering Department, Bechtel National Inc., and Praxair, Inc. LLNL's and Bechtel's designs and estimates were based on the use of commercially available turbines and other equipment. More accurate cost estimates based on our most up-to-date designs will be provided by our Conceptual Design Review report, to be completed during FY01.

A. Discussion of Factors Affecting the Cost of Carbon Dioxide Sequestration (Prepared by Clean Energy Systems.)

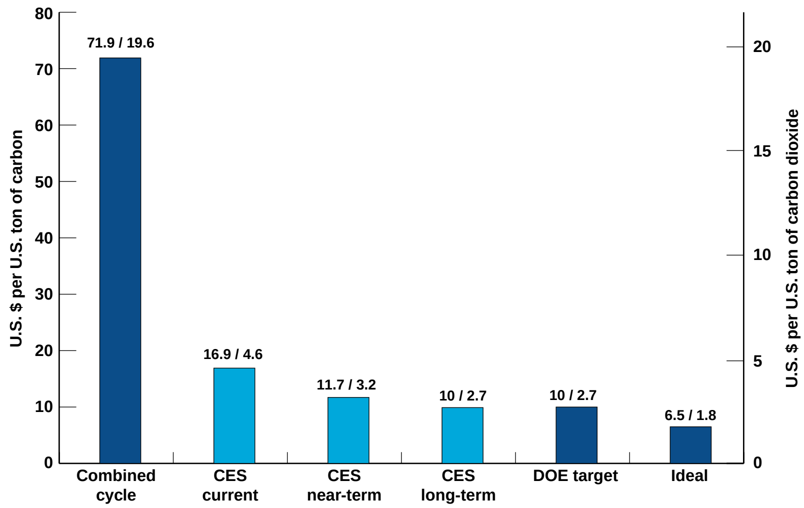
B. Bechtel Preliminary Design Study and Cost Estimate

Appendix A

Discussion of Factors Affecting the Cost of Carbon Dioxide Sequestration

Background

The cost of carbon dioxide sequestration was presented in a recent paper [1] [1]for a combined cycle and a cycle based on the Clean Energy Systems, Inc.[2] (CES) technology. The sequestration costs were given in a figure of the paper, which is reproduced below. This review presents the assumptions that were made to determine the sequestration costs.



Sequestration cost includes separating, liquefying and pumping CO_2 to 5000 psi (34.5 MPa). Compressor efficiency 80%, electric generator efficiency 98%, liquefaction coefficient of performance 3.0. Ideal cost assumes compressor, pump, liquefying and plant thermal efficiencies of 100%; Turbine technology for three turbine stages, I, II, III (pressure, temperature). **Current:** I (1200 psi (8.3 MPa), 1050°F (566°C)), II (141 psi (0.97 MPa), 1050°F (566°C), III (17.4 psi (0.12 MPa), 1050°F (566°C); **Near-term:** I (1500 psi (10.3 MPa), 1500°F (816°C)), II (165 psi (1.14 MPa), 2597°F (1425°C)), III (17.4 psi (0.12 MPa), 1050°F (566°C); **Long term:** I (3200 psi (22.1 MPa), 1796°F (980°C)), II (270 psi (1.86 MPa), 3200°F (1760°C), III (25 psi (0.17 MPa), 1796°F (980°C)

Figure 1: Comparative Cost of Carbon Sequestration for 100 MW Plants.

[1] Numbers in square brackets refer to references at the end of the report.

[2] Clean Energy Systems, Inc. (CES) 1812 Silica Avenue Sacramento, California 95815-3431, Phone: (916) 925-8206, Facsimile (916) 925-2135. Web address: http://www.cleanenergysystems.com

Several factors such as plant installation cost, amortization cost, fuel cost, maintenance cost, and plant efficiency enter into an economic analysis of an electric power plant. Although, in this review, we are interested only in the sequestration cost of the plant, nevertheless a number of the assumptions that enter into the economic analysis of the whole plant need to be considered in the sequestration part.

Sequestration Energy Requirements

The cost of exhaust gas sequestration includes the cost of separating the CO_2 from the turbine working fluid and pumping the CO_2 to a pressure of 5,000 psi. This pressure was chosen because it is sufficient to pump the CO_2 trough a pipeline of several miles and to pump the CO_2 into a subterranean formation at a depth of 5,000 ft.

Two sequestration cases will be analyzed. One case is for several CES plants and the second case is for a combined cycle plant.

In the CES plant, the working fluid leaving the turbines consists of a mixture of H_2O and CO_2. The mixture then is delivered to a condenser where the CO_2 separates from the H_2O. The pressure in the condenser is assumed to be 1.5 psi.

If the CO_2 were to be discharged to the environment, as would be done in a conventional plant, the pressure of the CO_2 would have to be raised from 1.5 psi in the condenser to atmospheric pressure. The energy required to raise the pressure of the CO_2 to atmospheric pressure is independent of sequestration options and therefore is charged to the cycle.

The energy required for CO_2 sequestration then is reduced to the energy required to increase the pressure of the CO_2 from atmospheric pressure to a pressure of 5,000 psi. All calculations are made for a methane flow rate of 1.0 lb/sec. The power of CO_2 compression will be expressed both in terms of kW per lb/sec of CO_2 and as kW per lb/sec of fuel.

We could increase the CO_2 pressure by compressing the CO_2 as a gas, or we could liquefy the CO_2 and then pump the liquid CO_2 to a pressure of 5,000 psi. We will consider first the option of compressing gaseous CO_2.

Table 1. Compression Power for CES Technology Based Plants

Power Required for Different Compression Stages		
Pressure ranges, Psi	Power, kW per lb/sec CO_2	Power, kW per lb/sec fuel
15 to 60	47	129
60 to 240	51	140
240 to 960	44	121
960 to 3840	34	94
3840 to 5000	6	17
Summary 15 to 5000	182	501

To raise the CO_2 pressure, we use five compression stages as shown in Table 1. The efficiencies of the compressors are assumed to be 80 per cent. As shown in Table 1, the power required for the gaseous compression of CO_2 is 501 kW per lb/sec of fuel.

To use a liquefying process, we first increase the pressure of the CO_2 from 15 psi to 145 psi using a gaseous compression process. The power required for this process is 240 kW per lb/sec of fuel. We then use a liquefaction process and assume a coefficient of performance of 3.0 for the liquefaction process. The power required to liquefy the CO_2 is 193 kW per lb/sec of fuel. Finally, we compress the liquid CO_2 to a pressure of 5,000 psi using 48 kW per lb/sec of fuel. The total energy required to increase the pressure of the CO_2 from 15 to 5,000 psi is 481 kW per lb/sec of fuel.

When we compare the power required to increase the pressure of the CO_2 from 15 to 5,000 psi, we note that the liquefaction approach requires 481 kW per lb/sec of fuel and the gaseous compression method 500 kW per lb/sec of fuel. The difference between these two methods is approximately 4 per cent, and either method could be used.

Combined Cycle CO_2 Sequestration Power

In the case of a combined cycle, the CO_2 first needs to be separated from the exhaust gases. We assume that the separation is 85 per cent effective. Thus, 15 per cent of the CO_2 generated by the plant would be emitted to the atmosphere. It is believed that increasing the separation effectiveness to a value greater than 85 per cent would make the process too expensive.

The separation of CO_2 from the turbine exhaust was studied by Falk-Pederson and Dannström [2] and C.A. Hendricks et al. [3]. Using the data from these references, we conclude, that the energy to separate the CO_2 at a pressure of 15 psi is 1,848 kW per lb/sec of fuel. To increase the pressure of the CO_2 from 15 psi to 5,000 psi was found above to be 481 kW per lb/sec of fuel. However, in the case of the combined cycle, the compression work is reduced because only 85 per cent of the CO_2 is sequestered. Hence, the compression work required is 409 kW per lb/sec of fuel. If we add this latter amount to the CO_2 separation energy of 1,848 kW per lb/sec of fuel, we obtain a total sequestration energy for a combined cycle of 2,257 kW per lb/sec of fuel.

In summary, for a CES plant, the power to sequester CO_2 of 481 kW per lb/sec of fuel corresponds to 97.2 kW-hr per ton of CO_2 and the power to sequester the CO_2 of a combined cycle is 456.0 kW-hr per ton of CO_2. In the next part of this report, these sequestration energy requirements will be translated into dollars and cents.

Sequestration Cost Evaluation

In a cost evaluation, we will consider 1) the capital cost of the plant, 2) the fuel cost and 3) the maintenance cost. These three costs form a basis from which the cost to generate electricity can be calculated.

Table 2. Capital Costs

Capital Cost for 100 MW plant, million$		
	CES plant 100% Sequestration	Combined Cycle plant 85% Sequestration
Steam turbine / generator	9.5	3.9
Gas turbine generator / generator	---	23.8
Condenser	0.7	0.3
Heat recovery steam generator	---	9.9
Cooling tower	1.8	0.8
Steam generator / reheater	2.6	---
Oxygen compressor	1.0	---
Natural gas Compressor	0.5	---
Transformer / switch gear	7.9	7.9
Balance of plant	7.4	7.4
Subtotal Equipment Cost, (EC)	31.4	54.0
Mech. & Electr. Construction (0.37 EC)	11.6	20.0
Engineering (0.08 EC)	2.5	4.3
Plant Construction Cost, no sequestration	45.5	78.3
Oxygen plant	25.9	
CO_2 Sequestration Equipment	---	14.9
CO_2 Compressor	1.0	0.9
Pipeline, drilling and completion of well	3.0	3.0
Total plant cost, including sequestration	75.4	97.1
Unit Cost, $ / kW including sequestration	754	971

The capital costs of 100 MW plants based on CES and combined cycle technologies are presented in Table 2. In Table 2, the cost of the sequestration equipment is included. The capital costs of the combined cycle plant were based on a scaled version of the actual costs of a 107 MW plant built at John F. Kennedy International Airport in Brooklyn New York [4]. The plant has two LM 6000 gas turbines at 40 MW and a steam turbine. The heat recovery steam generator is assumed to include NO_x scrubbers and CO fuel duct burners.

The turnkey 100 to 110 MW combined cycle plant prices range from $658/kWhr to $1,200/kWhr without sequestration. [4] The figures in Table 2 are within this range.

The cost figures of the combined cycle plant were compared also with data presented by Chiesa and Consonni for a 373 MW plant. [5] When these costs are scaled to a 100 MW plant the cost figures are respectively $823/kWhr and $1,225/kWhr for a combined cycle plant without and with sequestration.

Using cost figures by Simbeck [6] the scaled cost figures for a 100 MW plant without and with sequestration are found to be $635/kwhr and $1424 respectively.

In the cost figures of Table 2, the injection well is assumed to be located at, or near, the power plant site. Drilling and completion costs of the injection well with its surface equipment are estimated to be $0.8 million. In Table 2, a cost of $2.2 million is allocated for a CO_2 pipeline from the plant to the injection well.

Table 3 presents the efficiencies of the plants. In Table 3, the efficiency of the CES long-term data are based on a future oxygen separation technology, such as ion transfer membranes, that are assumed to produce a reduction in oxygen plant capital cost of 25 % and a reduction in oxygen separation cost of 50%.

Table 3. Efficiencies of Plants, Including Sequestration

Efficiencies based on lower heating value and including sequestration			
CES Current	CES Near-term	CES Long-term	Combined Cycle
31%	51%	66%	43%

If we assume that the plant life is 20 years, the interest rate is 11%, the utilization factor is 85% and the efficiencies of the plants are as indicated in Table 3, then we can determine the unit cost contribution of the electricity due to the capital investment. These unit capital costs are presented in Table 4 below.

The fuel unit costs are based on a lower heating value of 21,580 Btu/lb, a fuel cost of $2.50 per million Btu of fuel, and plant efficiencies as given in Table 3. The resulting fuel unit costs are given in Table 4.

Table 4. Unit Costs

Unit Costs of 100 MW plant, $ / kWh				
	CES current	CES Near term	CES Long-term	Combined cycle
Capital cost	0.013	0.012	0.012	0.017
Fuel cost	0.028	0.017	0.012	0.020
Maintenance cost	0.006	0.004	0.004	0.006
Total cost with sequestration	0.047	0.033	0.028	0.043

Unit maintenance costs are based on 15% of the sum of the capital and fuel costs. These unit maintenance costs are given in Table 4.

Using the cost figures of Table 4, we can determine the cost of sequestration either per ton of CO_2, or per ton of carbon. These costs are given in Table 5.

In Table 5, the CES plants emit no CO_2 to the environment and the combined cycle plant emits 15% of the plant's CO_2 to the environment.

Table 5 Sequestration Unit Costs

Sequestration Unit Costs per ton of CO_2 and per ton of carbon.				
Cost	CES Current	CES Near-term	CES Long-term	Combined Cycle
\$/ton CO_2	4.6	3.2	2.7	19.6
\$/ton carbon	16.9	11.7	9.9	71.9

Turbine efficiencies typically are based on the lower heating value of the fuel. The ratios of the sequestration costs of the CES and combined cycle technologies are independent of the use of either the lower or higher heating value of the fuel. However, in determining the overall cost of plant operation, the higher heating values should be used. Because fuel cost is only part of the overall plant operation cost, the actual costs are approximately 6% higher than the costs presented in Table 5.

Finally, the capital cost of a 100 MW combined cycle plant with sequestration as shown in Table 2 is approximately 20 to 30 % lower than the data presented in References 5 and 6.

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Appendix B

Preliminary
Design Study and Cost Estimate
for
Zero Emission Steam Technology
Research Facility

Letter Report Study

June 30, 2000

Lawrence Livermore National Laboratory

Prepared by
Bechtel National Inc.

1.0 Introduction

Lawrence Livermore National Laboratory (LLNL) has initiated a research and development project on a technology for production of electric power with no emission of exhaust gases to the atmosphere. Bechtel was asked by LLNL to conduct a design study of a Zero Emission Steam Technology (ZEST) Research Facility to be built at the LLNL. The objectives of this report are to identify plant equipment and facilities at a preconceptual level and to provide a rough cost estimate for project planning purposes. The results of this report will be used to support a more detailed conceptual design report.

This report presents preliminary design information and cost data that were developed based on design criteria and information provided by LLNL and Clean Energy Systems, Inc (CES). Technical and cost issues are also examined in the report for future consideration. This study was completed in 6 weeks.

Major design bases and assumptions include:

- The facility will be located on the LLNL site and Greenville oil field site.
- The process design is based on the flowsheet and mass balance by CES (see Appendix A).
- The fuel source will be natural gas. Oxygen for combustion will be supplied from an on site oxygen separation plant.
- Natural gas, oxygen and water will be injected in a gas generator for combustion
- The combustion gaseous mixture will be fed through a three-stage turbine connected to an electrical generator to produce electricity.
- Nominal electrical power output will be 5 MW net. Subject to DOE approval, the electricity produced will be retured to LLNL's power grid and used at the lab.
- Carbon dioxide from combustion will be compressed, pumped through a pipeline to an oil field northeast of LLNL, and injected underground into the Greenville formation.
- The facility will be operated on a 3-month on and 3-month off basis, equivalent to 4,380 hours per year.
- Only two full-time employees are included in the operations cost estimate. A research program budget will cover the cost of other required employees.
- The LLNL site will have sufficient electrical power capacity for plant start-up and shutdown.
- The design will consider future expansion with a turbine generator system of higher temperature and pressure.

2.0 Summary of Results

The Zero Emission Steam Technology Research Facility has a gas generator-turbine system with 15.7 MW thermal input and generating 7.9 MW of electricity. After accounting for plant equipment power usage, the nominal net power output of the plant is 5 MW. About 15,000 tons/yr of carbon dioxide (CO_2) exhaust will be injected into the oil field formation at 1000 psia. The facility, which includes an oxygen separation plant, occupies about 1.5 acres at the LLNL. Rough sizes of major equipment, the process building and support facilities were calculated from the preliminary conceptual design information.

The preliminary estimated total construction capital cost is $62 million. This includes $48.1 million for plant facilities; $6.5 million for the pipeline, injection well system, and oil field facilities; and $7.4 million for design and engineering. These costs are in current (June 2000) dollars. The capital cost escalated to midpoint of construction (March 2004) is $68 million.

The annual operating cost is about $550,000. This cost includes 2 full time employees and revenue from sales of electricity which offsets some operating cost. But does not include other program personnel (scientists, technicians, maintenance, etc.) or oil field leasing or royalties.

The preliminary schedule assumes selection of an architect/engineer (A/E) contractor in mid 2002. The schedule shows engineering design starting in October 2002, construction beginning in October 2003, and operations beginning in September 2005. The schedule assumes that no funding restraints will curtail project activities.

The Zero Emission Steam Technology is more complex than a conventional combined cycle turbine technology. The gas generator, steam turbine system, and condenser are critical plant systems. These plant systems must be fully integrated and may require a complex control system. Further review of these systems is necessary to facilitate a more detailed facility design.

It is suggested that a simulation program be used to fully analyze gas/fluid flow. Among considerations are the stoichiometry of oxygen and natural gas combustion, CO_2, N_2 and steam content.

Fuel feed systems must be clean and therefore natural gas, oxygen and water system cleanliness requirements need to be verified.

The cost of oxygen separation is an important element to be reviewed. Also, the possible use of steam injection into the oil wells, efficient use of water and the sale of CO_2 or N_2 will also have an effect on cost. Materials of construction for the various systems and equipment need to be established.

Geological sequestration of CO_2 and enhanced oil recovery are both active research topics supported by US DOE Fossil Energy programs. The Livermore Oil Field is located near the proposed site for the ZEST Plant. The Livermore Oil Field consists of about a dozen oil wells and has been producing oil from a sandstone formation that is about 1600 feet below the surface. This oil field began producing in the late 1960's. This oil field lies in the active seismic fault zone of the Greenville Fault System.

The plan for ZEST includes tertiary CO_2 injection (or flood) into the producing formation or oil reservoir. This CO_2 will be injected with well-head pressure of 500 psi to 700psi to help repressurize the oil reservoir and enhance oil production by sweeping more of the remaining oil out of the reservoir. It is important to monitor the CO_2 flooding front and to control the pressure and volume of CO_2 into the tertiary injection well. Various sensors and controls will be installed into the injection well and in the monitoring wells to provide this information and control. Geological, geochemical, and geophysical modeling and analysis will help provide input to basin or reservoir simulators to help optimize the tertiary oil recovery research as well as the CO_2 sequestration.

The zero emission technology is in developmental stage and there is little existing data available to evaluate the economics of this kind of plant. Therefore, cost data generated from detailed design, construction and operations of this facility, would be very valuable, in assessing the economic viability of a scaled-up industrial plant based on zero emission power generation technology.

3.0 Facility Description

3.1 Process Description

Natural gas and oxygen are burned and mixed with water to produce steam and carbon dioxide. This mixture drives a three-stage turbine connected to an electrical generator to produce electricity. The turbine exhaust is cooled in a condenser. The condensate is recycled back to the gas generator. Excess condensate is bled off and discharged to sewer. The carbon dioxide is compressed and pumped via a pipeline to an oil field for injection into the ground.

The major systems are the oxygen plant, gas generator (i.e., combustor/steam generator), steam turbine and electrical generator, condenser and condensate system, carbon dioxide compressors, pipeline, and injection well. Process flow diagrams are shown in Figures 1 to 4. A list of major equipment is shown in Appendix B.

Oxygen is produced on site using a cryogenic distillation process that separates oxygen from air. The oxygen gas is supplied to the number 2 turbine reheater at 30 psia and compressed and fed to the number 1 turbine reheater at 160 psia.

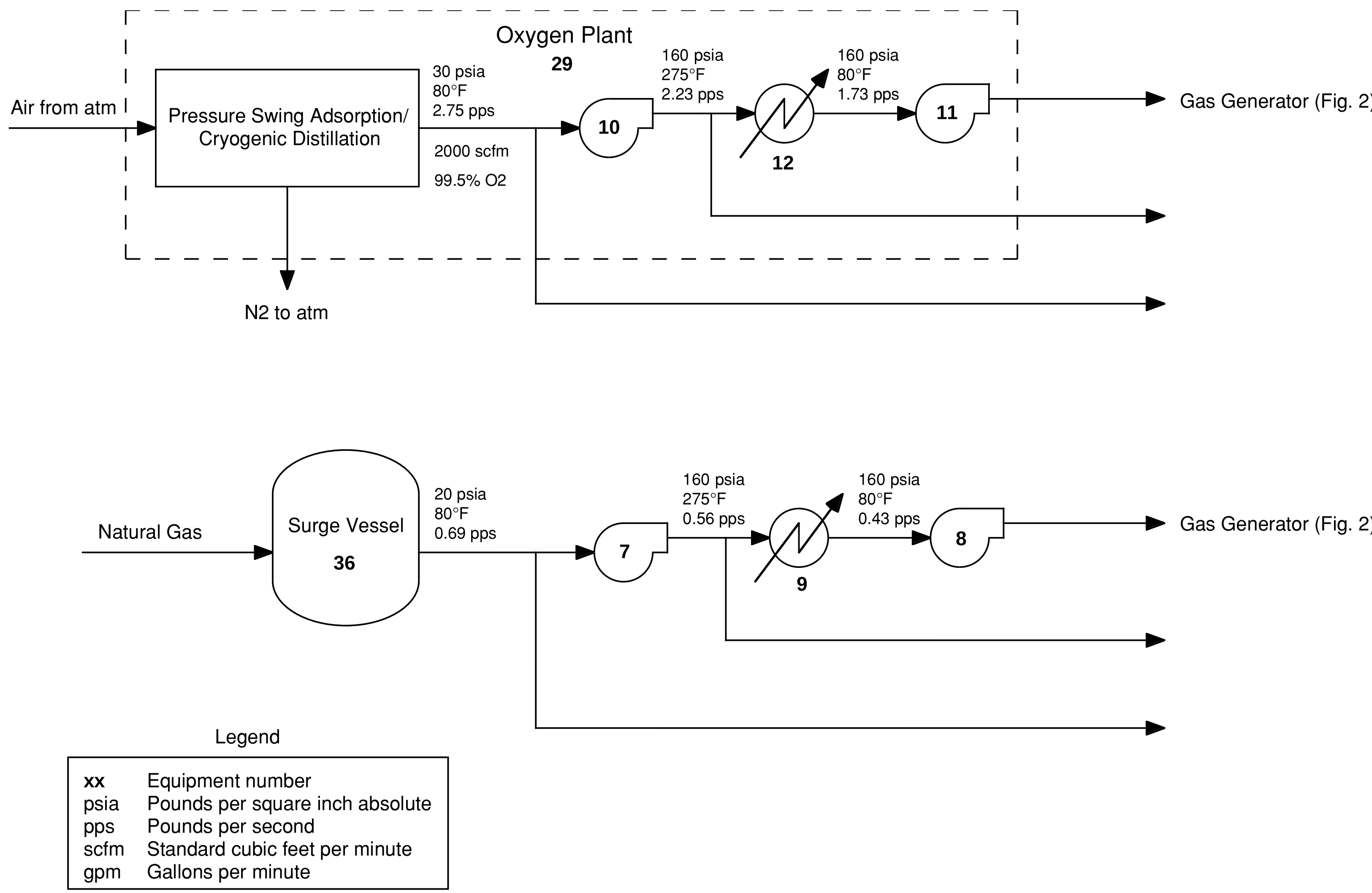

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Figure 1 Oxygen Plant and Natural Gas System

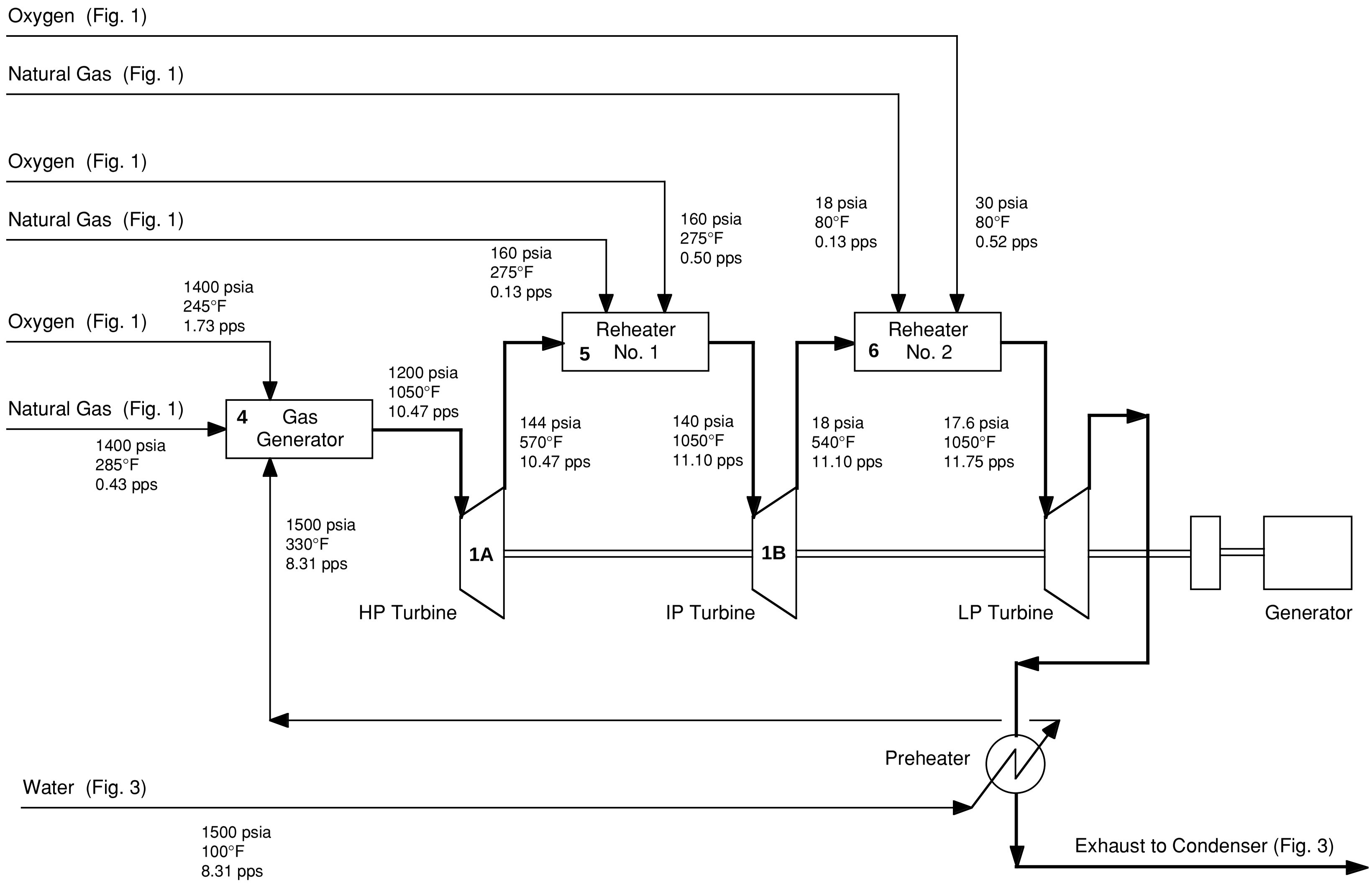

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Figure 2 Combustion Turbine

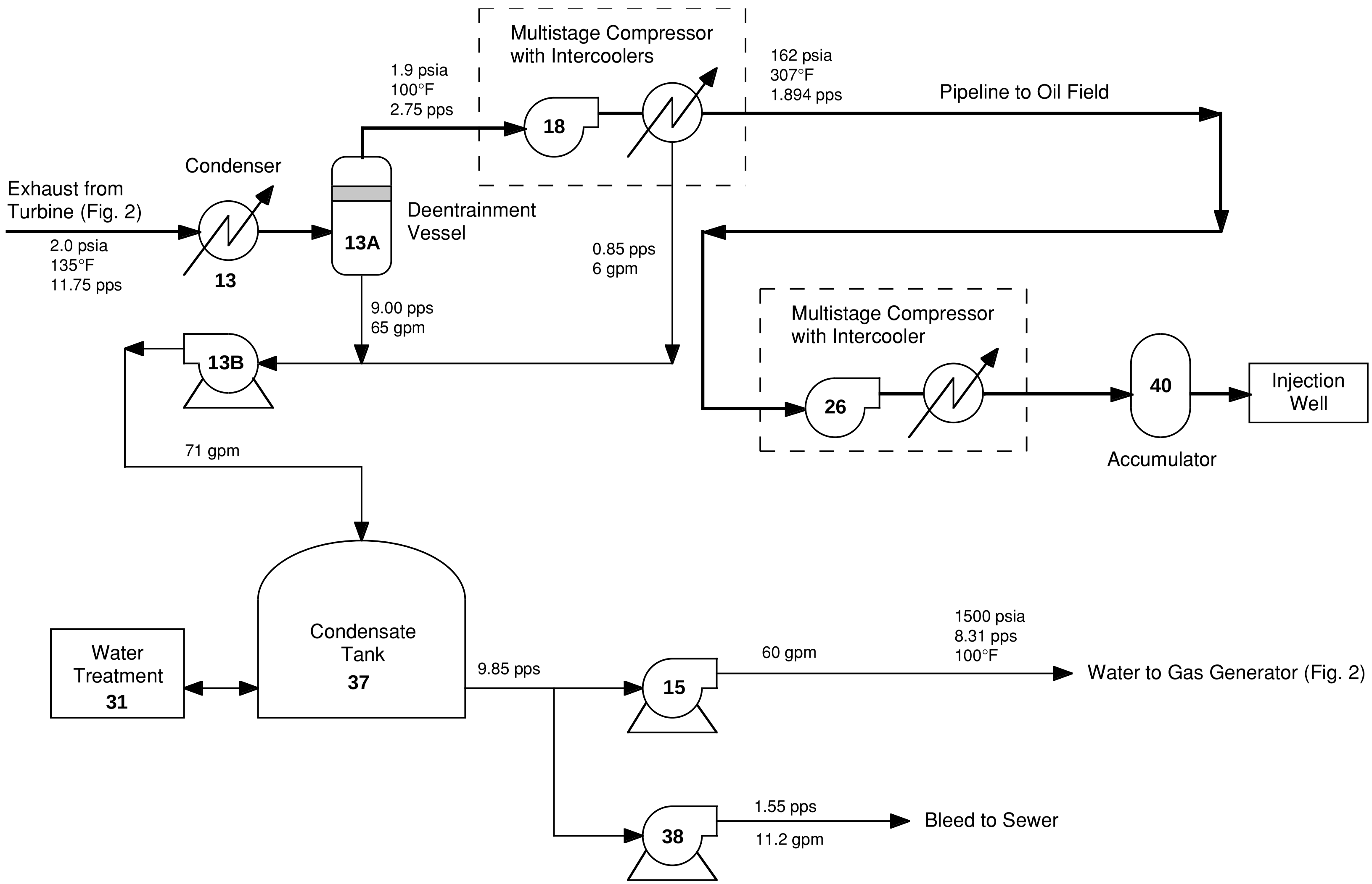

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Figure 3 Turbine Exhaust and CO2 to Well

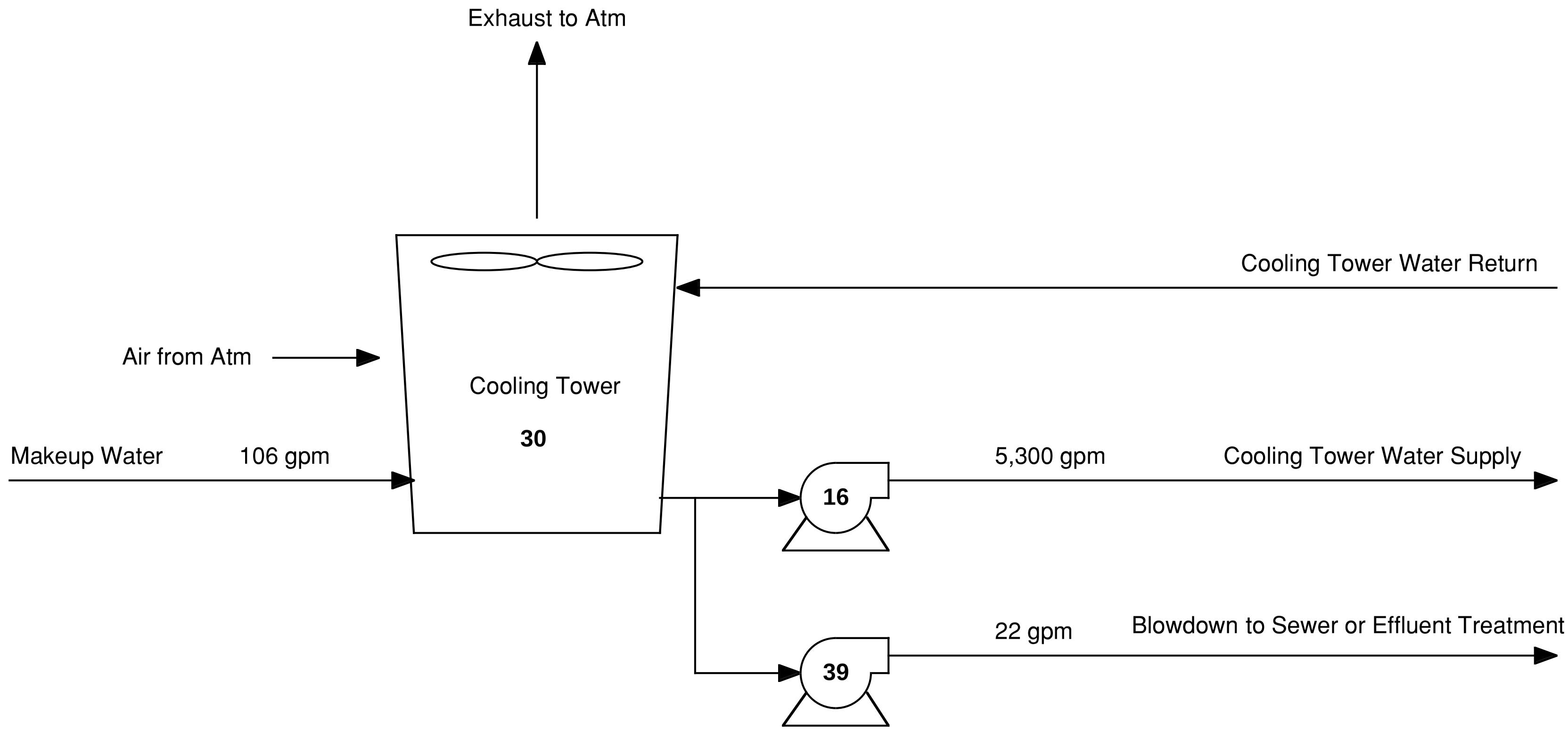

Figure 4 Cooling Tower Water

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Oxygen gas is compressed to 1,400 psia for feed to the gas generator. The nitrogen gas byproduct from the oxygen plant operation is vented to atmosphere.

Natural gas from the local utility company is supplied to the number 2 turbine reheater at 20 psia and compressed and fed to the number 1 turbine reheater at 160 psia. Natural gas is compressed to 1,400 psia for feed to the gas generator.

A high pressure water pump supplies feed water to the gas generator at a pressure of 1500 psia.

The natural gas and oxygen are injected and mixed in the gas generator, where they burn to produce heat, carbon dioxide and water vapor. Water is injected into the gas generator to cool the mixture and to produce steam. The resulting steam and carbon dioxide mixture (nominally 1200 psia 1050°F) passes through a three-stage turbine which is connected to an electrical generator. Reheaters burning natural gas and oxygen are provided between the turbine stages.

After the third stage turbine, the exhaust passes through a preheater that heats the feed water to the gas generator. The exhaust then flows to the condenser and deentrainment vessel, where most of the steam is condensed and separated from the carbon dioxide gas. Remaining water vapor is condensed out in subsequent compressor intercoolers. The condensate is collected and supplied to the high pressure water pump for recycle to the gas generator. Because the combustion reaction produces water, excess condensate is bled off and discharged to the LLNL sewer. This bleed stream also limits the buildup of impurities in the recycle condensate. A sidestream of condensate can be treated to further maintain water quality.

The carbon dioxide gas is compressed to about 160 psia using a multistage compressor. Intercoolers between the stages cool the gas and remove additional moisture. The carbon dioxide gas is fed to a 1.9 mile long, 3 inch diameter stainless steel underground pipeline to the oil field. At the oil field, the carbon dioxide is compressed to 1000 psia and injected into the oil formation.

Materials of construction are stainless steel for wet carbon dioxide, stainless steel or high nickel alloys for oxygen, and carbon steel for natural gas. It is assumed the condensate system will require corrosion-resistant materials such as stainless steel or plastics to maintain water quality.

An evaporative cooling tower supplies cooling water to the turbine condenser. Small amounts of cooling water are also supplied to compressor intercoolers, aftercoolers, and miscellaneous equipment. Makeup water is supplied from the LLNL water system and cooling water blowdown water is discharged to the LLNL sewer system.

Major plant input and output quantities are summarized in Table 1.

Table 1 Major Plant Input and Output Streams

Major Input Streams	Major Output Streams
Natural Gas 223 million std. cubic feet/yr (2.34 million therms/yr)	Carbon Dioxide 15,000 tons/yr
Oxygen (from oxygen plant) 21,681 tons/yr	Nitrogen (to atmosphere from oxygen plant) 71,367 tons/yr
Makeup Water to Cooling Tower 28 million gallons/yr	Excess Condensate Water (from condenser) 2.9 million gallon/yr
	Cooling Tower Blowdown Water 5.8 million gallons/yr

Initially, the electrical generator will produce about 7.9 MW electric power with a 15.7 MW thermal power input to the turbine system. The ZEST facility will consume about 3.5 MW of electricity, resulting in a net energy production of 4.4 MW. The major consumers of electrical power are 1500 kW for oxygen separation, 400 kW for oxygen compression, and 900 kW for the CO2 compressors. The plant operation is monitored by a computer based control system located in the plant facility.

3.2 Plant Facilities

The major facilities to be constructed will be located at the LLNL site. A site location in the MFE Capacitor DC Power Area adjacent to Building 531 has been tentatively identified for the plant construction. Additional construction will occur at the oil field and along the pipeline from the LLNL site to the oil field. An injection well system for CO2 will be built at the oil field northeast of the LLNL. A project location map and site aerial photograph are shown in Figures 5 and 5A, respectively.

The ZEST facility at LLNL occupies about 1.5 acres and includes a Process Building, oxygen plant, and support facilities. The site plan considers future expansion of the Process Building to accommodate a turbine generator system of higher temperature and pressure. A conceptual site layout is shown in Figure 6.

The Process Building is a steel frame, metal structure with a 2 ft thick concrete mat foundation. The 50 ft x 140 ft building is 30 ft high in the turbine/generator area and 20 ft high in the compressor area. The building is ventilated and lighted, but no

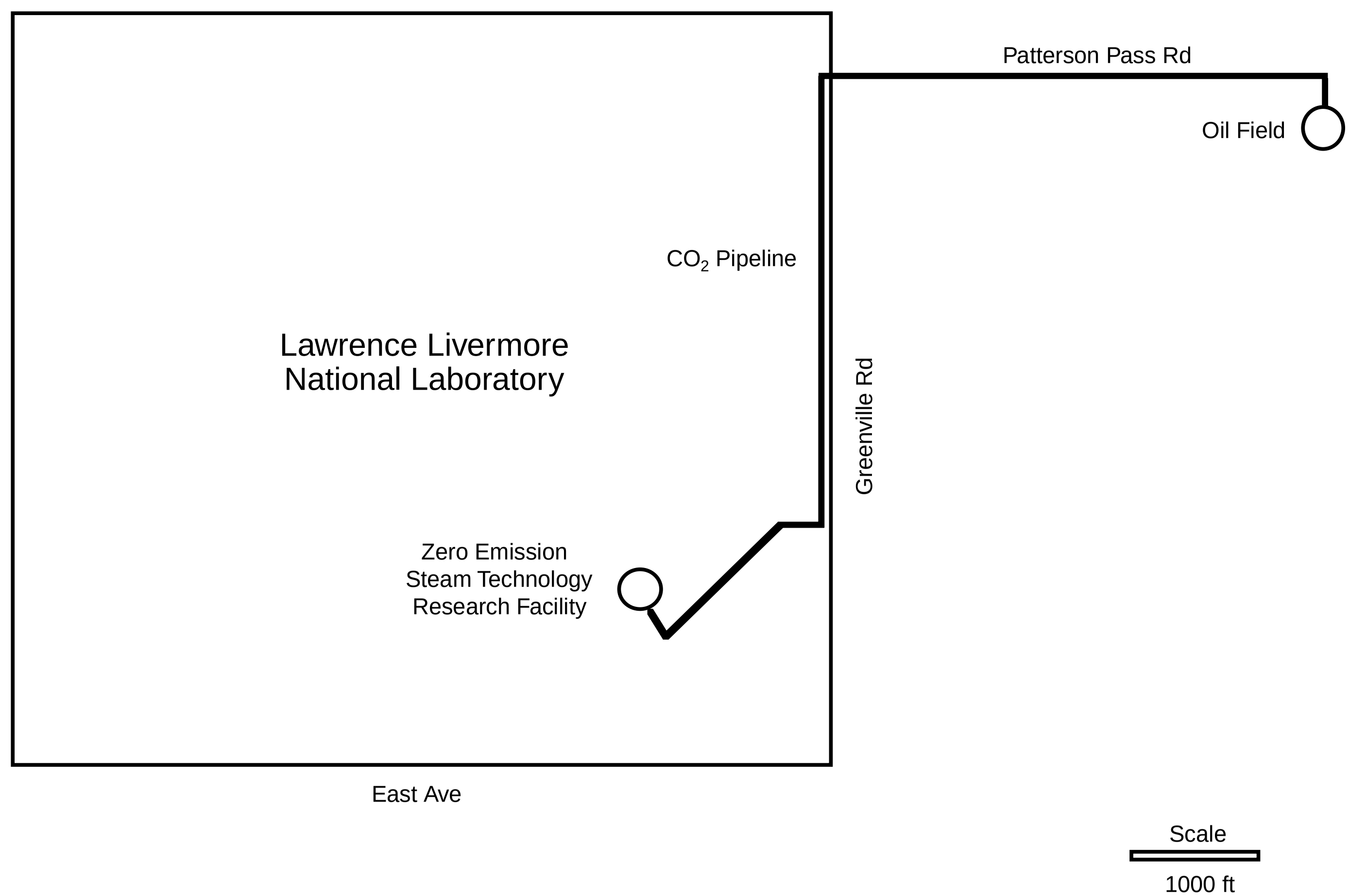

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Figure 5 Project Location Map

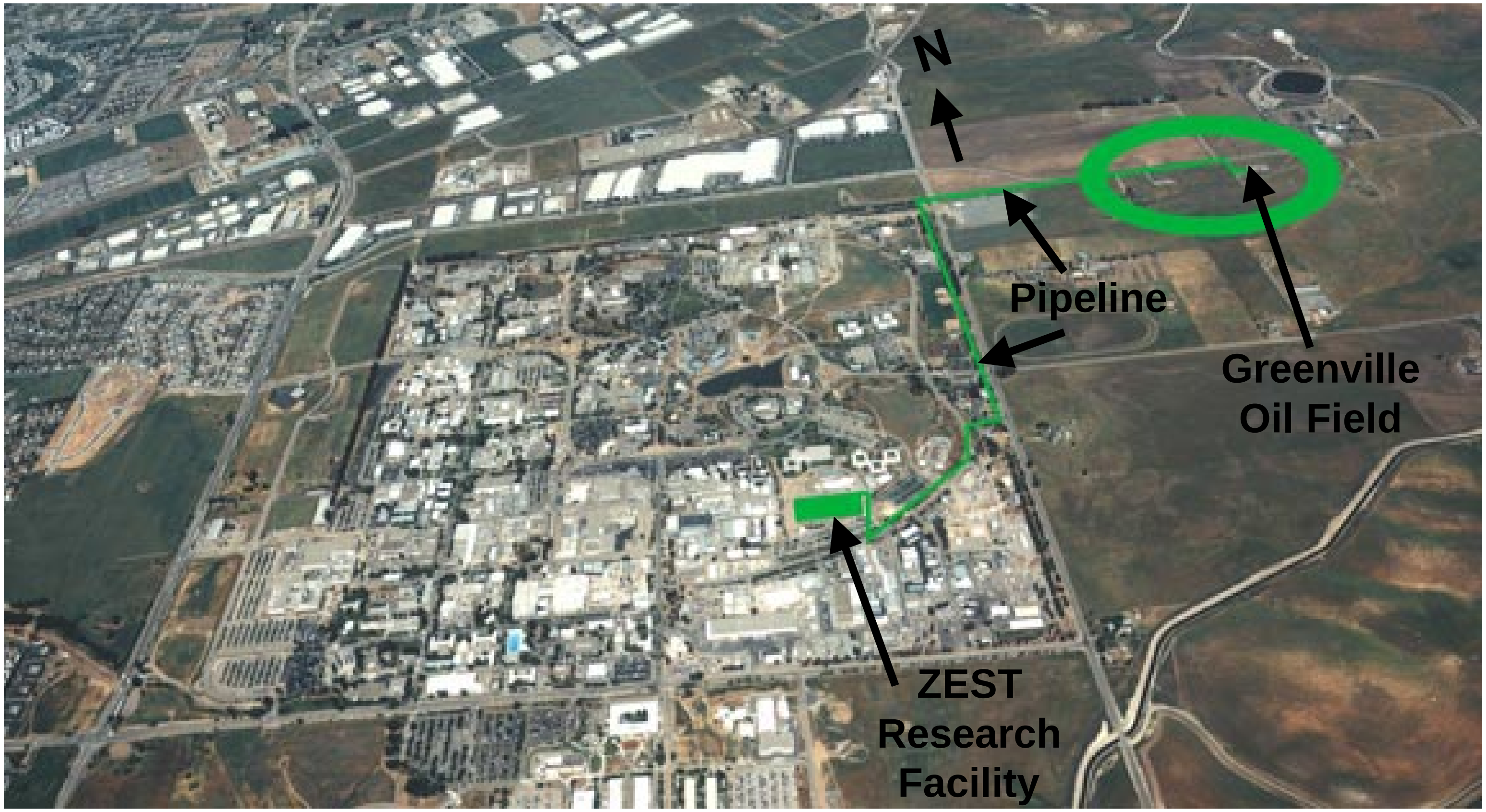

Figure 5A ZEST Research Facility Site Aerial View

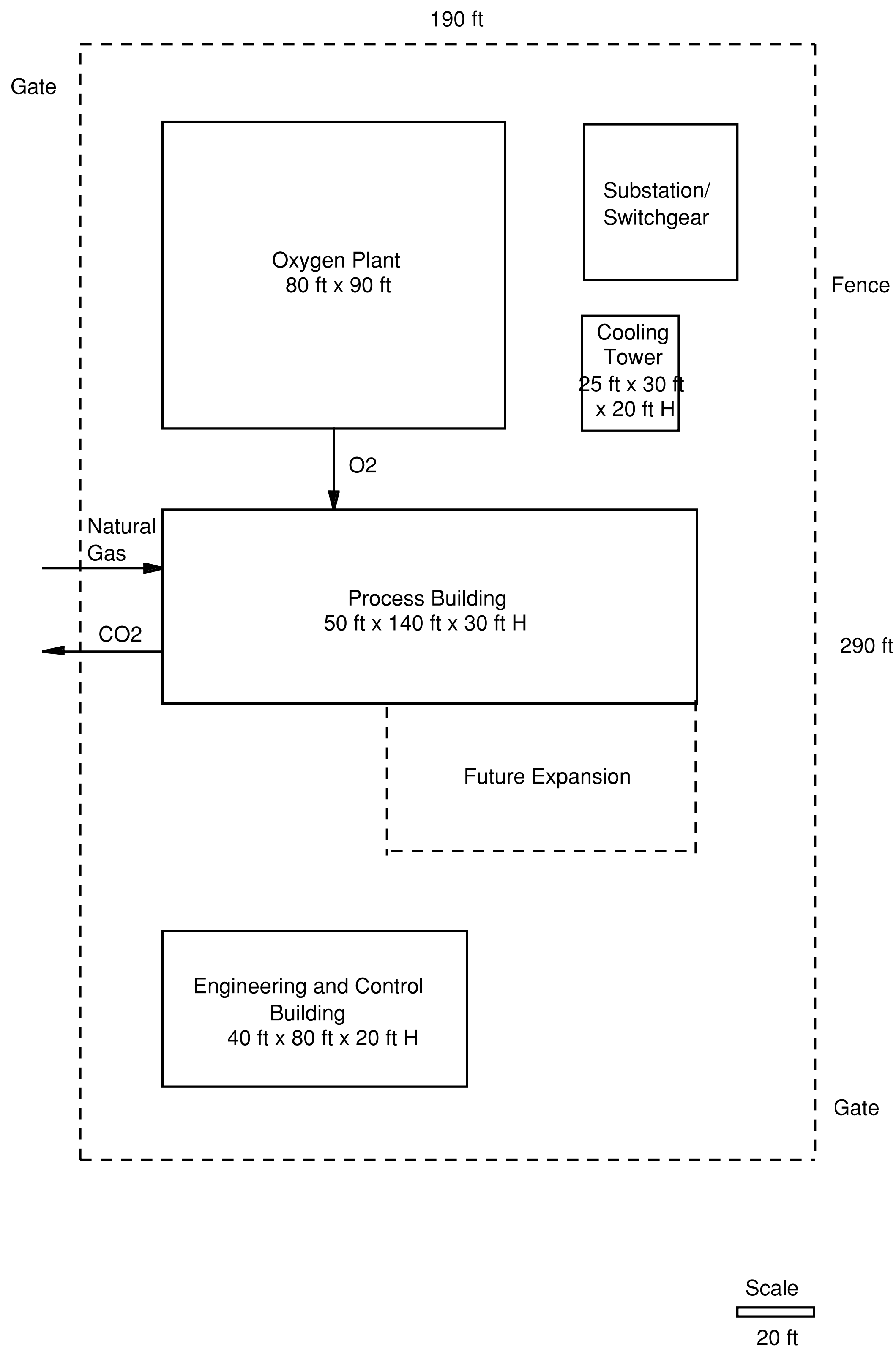

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Figure 6 Site Layout at LLNL

heating or cooling is provided. A 40 ft high vent stack is provided to discharge exhaust gases to atmosphere during startup, shutdown and upsets. The facility will be designed and constructed in compliance with DOE Orders and applicable regulations and codes. In the absence of a hazard analysis, it is assumed that the Process Building is performance category PC-1. A conceptual Process Building general arrangement is shown in Figure 7.

Support facilities at the LLNL site includes an Engineering and Control Building and cooling tower pad, electrical switchgear, substation, and a security fence.

The Engineering and Control Building is 40 ft x 80 ft and houses the control room, offices, storage and maintenance areas. The building is a prefabricated modular building with conventional HVAC for personnel comfort.

The injection well system includes one CO2 injection well and four monitoring wells to be drilled at the Greenville oil field site. The injection well is 2000 ft deep with a casing size of 5 1/2 inch. Each monitoring well is 3200 ft deep with a casing size of 8 5/8 inch.

Oil field facilities include a CO2 injection pump station and four monitoring stations near the well heads. The injection pump station has a 20 ft x 20 ft metal building with final-stage compressor and equipment. Each monitoring station is provided with a small (15 ft x 15 ft) metal building to house monitoring equipment.

The plant will be operated on a cycle of 24 hours/day and 7 days/week for a duration of three months for testing and demonstration runs, followed by a three month shutdown.

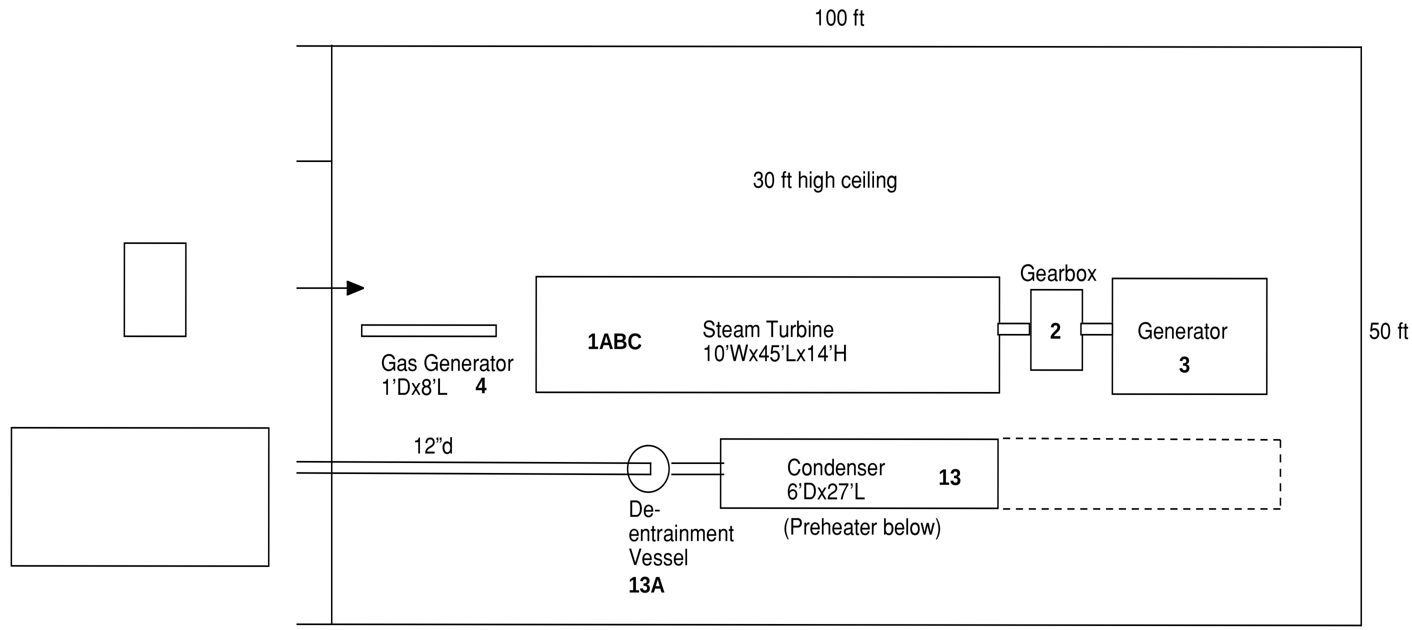

Figure 7 Process Building Layout

3.2 Cost Estimates and Schedule

The cost estimates are rough order of magnitude estimates based on preconceptual design information. Results of the capital cost and of operating cost estimates are summarized in Table 2.

Table 2 Cost Estimate Summary
(June 2000 dollars)

	Cost ($million)	Contingency ($million)	Total Cost ($million)
Engineering	**5.5**	**1.9**	**7.4**
Plant Facility			
Process Equipment & Oxygen Plant	27.0	9.5	36.5
Process Facilities	2.6	0.9	3.5
Support Facilities	1.3	0.4	1.7
LLNL Site Prep & Tie-in	4.73	1.66	6.4
Plant Facility Total	**35.6**	**12.5**	**48.1**
Pipeline and Well Systems			
CO2 Pipeline	1.97	0.69	2.66
Injection Well System	2.08	0.73	2.81
Oil Field Facilities	0.75	0.26	1.02
Pipeline and Wells Total	**4.8**	**1.7**	**6.5**
Total Capital Cost	**45.9**	**16.1**	**62.0**
Annual Operating Cost	**0.55**	--	**0.55**

The preliminary estimated total construction capital cost is $62.0 million. This cost is based on current (June 2000) dollars. The capital cost escalated to midpoint of construction (March 2004) is $68.2 million, based on DOE's cost index.

The estimates are based on the labor cost in the San Francisco Bay area and include indirect cost factors for a LLNL project. The cost estimates for the LLNL site preparation and utility tie-in and the CO2 pipeline were furnished by LLNL. The costs for the gas generator and oil well system subcontract were furnished by CES. The oxygen plant cost is based on a subcontract that includes materials, installation and startup by an oxygen vendor. Cost estimate basis and details of the cost estimate results are shown in Appendix C.

The construction capital costs are based on an engineering, procurement and construction management (EPCM) approach. The capital cost estimate utilized budgetary quotations, estimating manuals, allowances, and historical cost data. A 35% contingency was applied to the capital cost. This contingency level is based on previous risk analysis on projects of similar scope and level of design details. Costs excluded from the estimate are technical design data development, oil field land lease, royalties, R&D cost, DOE oversight, and facility removal and site restoration after project completion.

The operating cost includes costs for natural gas, consumable materials, utilities, and operating labor, and revenue from sales of electricity. Two full-time employees are costed for plant operations. Due to the research nature of plant operations, research staff and other required employees are not included in the operating cost. The research program budget will cover the cost of other required employees.

Subject to DOE approval, revenue from sales of electricity is estimated to be $1.0 million annum based on 3¢ per kWh. The revenue is credited to offset the operating cost. Potential revenue from CO2 sales is excluded.

The preliminary project schedule is shown in Figure 8. The schedule assumes selection of an A/E contractor in mid 2002. The schedule allows 15 months for engineering design starting in October 2002 and 21 months for construction beginning in October 2003. Plant operations would begin in September 2005. The schedule assumes that no funding restraints will curtail construction activities throughout the project duration.

5.0 Discussion and Issues

Several technical issues have been identified during the course of this study which will require further investigation in the next CDR design phase.

5.1 Process Equipment

The facility will utilize newly developed equipment and demonstrate a new technology. The most important equipment issues include:

- The process utilizes a gas generator for combustion and steam generation. The gas generator is currently under development by CES and is critical to the design.

- The plant system is more complex than a conventional combined cycle turbine system. Any gas fluctuation will have impact on stability of downstream equipment operations. Startup and control of the process should be simulated before plant operation.

Activity ID	Activity Description	Duration Month	Early Start	Early Finish
MILESTONES				
1	Select A/E Contractor			30SEP02
2	Authorize Construction			31MAR03
3	Select Construction Contractors			30JUN03
4	End of Construction			30JUN05
5	Operation Reviews			30SEP05
6	Start-up & Operations			30SEP05
PROJECT MANAGEMENT				
1	Project Definition	10	01MAY00	30SEP00
2	DOE Action	9	01OCT01	30JUN02
3	Contractor Evaluation	6	01APR02	30SEP02
4	Permitting & Licensing	36	01OCT02	30SEP05
DESIGN / ENGINEERING				
1	Conceptual Design	9	01OCT00	30JUN01
2	Preliminary Design (Title I)	6	01OCT02	31MAR03
3	Detailed Design (Title II)	12	01JAN03	31DEC03
4	Construction Support (Title III)	24	01JUL03	30JUN05
PROCUREMENT				
1	Procurement	27	01APR03	30JUN05
CONSTRUCTION				
1	Power Plant Facility	21	01OCT03	30JUN05
2	Pipeline and Injection Well Systems	15	01APR04	30JUN05

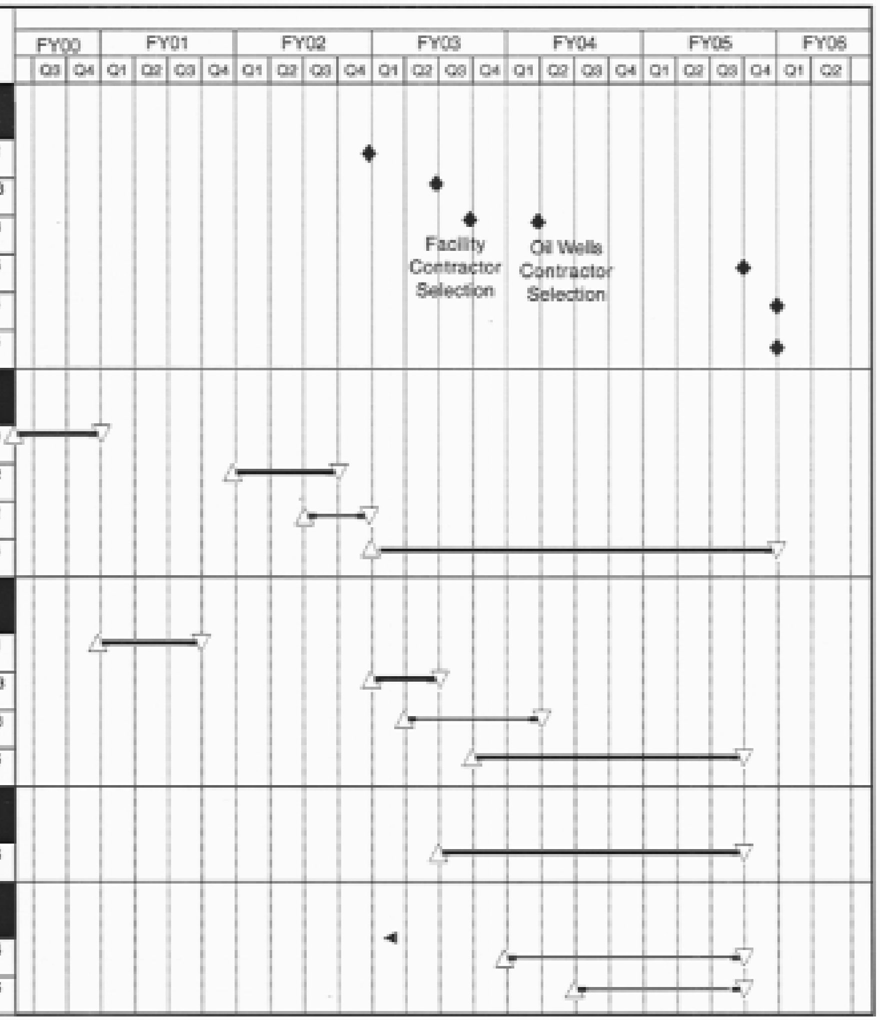

Figure 8
Zero Emission Steam Technology Research Facility
Preliminary Project Schedule

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Potential areas of study concerning the oxygen plant include:

- The reliability of the oxygen plant and stability of the oxygen pressure is a concern. A surge and backup source of oxygen should be considered.

- The oxygen plant could be deleted and replaced by storage tanks for liquid oxygen delivered by truck.

(The cost would be about $.35/100 cf and a $5000/month equipment rental fee. At an oxygen consumption rate of 25,000 gallons/day, or 2.75 lb/sec for 4380 hrs/yr, the cost is $1.85 million/yr. For comparison, the cryogenic plant cost is about $7.5 million plus $380,000 per year for electricity, based on 1900 kW for 4380 hrs at 4.6¢/kWh.)

- Oxygen separation is based on cryogenic distillation process in this study. The use of 90-94% purity oxygen produced by a vacuum pressure swing adsorption system could be studied. This system has a lower capital cost ($5.8 million vs. $7.5 million for cryogenic plant), but potentially some nitrogen will be converted to undesirable nitrogen oxides in the gas generator, and the greater gas flow will increase some equipment sizes.

- The effect of excess oxygen needed to assure complete combustion must be considered in future process design and detailed equipment sizing.

Other potential areas of study include:

- The cleanliness of gases and water feed is critical to the gas generator operation because particle impurities in the feed may cause system plugging. Adding a second parallel gas generator should be considered in the design.

- Water purity requirements for the gas generator, turbine and condenser systems need to be defined to determine what if any treatment is necessary to enable condensate to be recycled as feed water to the gas generator.

- The design of turbine exhaust condenser will need particular effort because the presence of non-condensable CO_2 gas will significantly decrease the overall heat transfer coefficient and increase the exchanger area required.

- In this study, an evaporative cooling tower was selected in the cooling water system. An alternative is a dry cooling tower that has zero discharge of blowdown water and requires no makeup water. The cooling water supplied from a dry cooling tower can be as warm as 120°F or higher. This would require a change in the condenser operating temperature and its impacts on plant energy efficiency and cost need to be reevaluated.

- Additional study is needed to determine the suitability of the chosen materials for corrosion resistance.

- Surge and storage vessels in the plant system design need further evaluation.

5.2 Site and Facility

The Process Building, which houses the turbine, generator and compressors, was assumed to be performance category PC-1 (UBC industrial type). A safety and accident analysis is required to determine the hazard classification and performance category.

Further study is needed to establish the Process Building size and appropriate structure for weather protection and noise abatement. The possibility of eliminating the building and installing the turbine and compressors outdoors under a rain cover needs study.

This study assumed a site location adjacent to Building 531. Exact location of the facility must be determined with consideration of pipeline connection and noise issues.

Further study is needed to confirm the feasibility of transmitting excess power produced at the plant back into LLNL's power grid without impacting its stability and reliability.

Geotechnical and other issues concerning oil well drilling and CO2 injection into underground formation are not covered in this study, and may need examination.

5.3 Cost Estimate and Schedule

Major equipment costs are based on rough equipment sizing with engineering judgment and budgetary quotations from vendors with incomplete engineering data. Additional design is needed to allow a more accurate pricing.

The major contributors to the capital cost are the oxygen plant and steam turbine. A survey from several turbine manufacturers has been conducted. A turbine with the actual two-reheater design is found not available and the information collected is inadequate for estimate purpose. The steam turbine in the estimate is based on MW rating of the turbine. Further cost confirmation and validation is required.

Cost for the oxygen plant is based on a vendor supplied and installed plant. Capital cost can be reduced if the oxygen plant is leased from the supplier. The oxygen plant could even be operated by the vendor, who would then sell the oxygen on a dollars per cubic foot basis. These alternatives were not addressed in this study.

The schedule shows a construction start in October 2003. This appears to be attainable if early approval for construction dates are met. The steam turbine and compressors are on critical path of the construction and their procurement generally requires 12-24 month lead time. Early procurement of long-lead equipment items is required to meet the schedule.

5.4 Economics

The plant produces a fairly pure nitrogen gas byproduct from the oxygen plant. The nitrogen is vented to atmosphere. If the economics are favorable, the nitrogen could be compressed and distributed to users at the laboratory.

The plant also produces a fair amount of steam (35,000 lbs per hour) from the combustion process, the economics of steam injection to oil field formation to enhance oil and gas recovery need to be examined.

The ZEST facility has been sized on a nominal 5 MW capacity for technology demonstration, and therefore, the economic viability of a zero emission power plant has not been assessed in this study. An economic analysis to be based on a design study of a scaled-up industrial plant is necessary to address this issue.

Appendix B.1

Zero Emission Steam Technology Research Facility

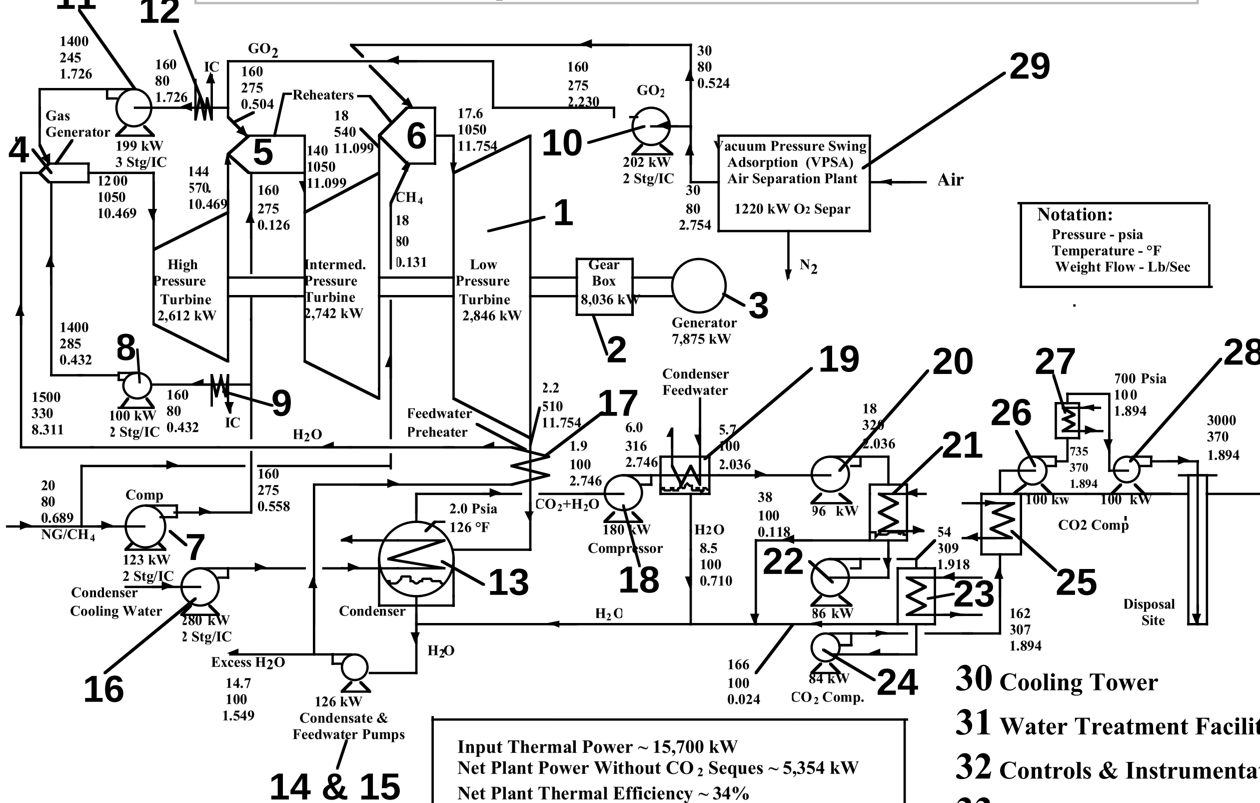
Flowsheet and Mass Balance

by

Clean Energy Systems, Inc.

CES 5 MW Zero Emissions Power Plant

(*Components & Cost Items*)



Input Thermal Power ~ 15,700 kW
Net Plant Power Without CO_2 Seques ~ 5,354 kW
Net Plant Thermal Efficiency ~ 34%
Net Plant Power With CO_2 Seques ~ 5,000 kW
Net Plant Thermal Efficiency ~ 32%
LHV CH_4 = 21,518 Btu/lb, Comp/Pump Eff. = 75%
Combustor Pressure Loss = 2.5 %, HX = 5 %

30 Cooling Tower
31 Water Treatment Facility
32 Controls & Instrumentation
33 Switch Gear
34 Transformers
35 Data Aquisition System
36 Balance of Plant ~ 16% x Equip Cost (1thru 35)
37 Net Equip Cost = Items 1 thru 36
Engineering ~ 7% x Net Equip Cost
Mech & Elect ~ 100% x Net Equip Cost
Total Plant Cost ~ 207% x Net Equip Cost

CES
3/12/99
LS47%

Appendix B.2

Major Equipment List

for

Zero Emission Steam Technology Research Facility

MAJOR EQUIPMENT LIST
ZEST Research Facility

Equipment No.	EQUIPMENT DESCRIPTION	Quantity	Equipment Size or Power	Design Parameters
1A	High Pressure Turbine	1		Pi=1,000-1,200 psia, Ti=900-1,050°F, Flow=45,000 lb/hr
1B	Intermediate Pressure Turbine	1		Pi=130-160 psia, Ti=900-1,050°F, Flow=45,000 lb/hr
1C	Low Pressure Turbine	1		Pi=15-18 psia, Ti=900-1050°F, Flow=45,000 lb/hr
2	Gearbox	1		Input speed 6,000 rpm, Output speed 3,600 rpm, power 8 MW
3	Electrical Generator	1	7.9 MW	
4	Gas Generator	1	1'-0" D x 8'-0"L	
5	Reheater No.1	1	Diameter 6"	Pi=146 psia, Po=142 psia, Ti=570°F, To=1,050°F
6	Reheater No.2	1	Diameter 18"	Pi=16.5 psia, Po=16.0 psia, Ti=570°F, To=1,050°F
7	CH4 Compressor #1	1	148 BHP	Pi=20 psia, Po=160 psia, 0.56 lb/sec, 2 stage reciprocating, includes intercooler
8	CH4 Compressor #2	1	122 BHP	Pi=160 psia, Po=1400 psia, 0.43 lb/sec, 2 stage reciprocating, includes intercooler
29	Oxygen Plant	1	1500 kW	2.75 lb O2/sec, Cryogenic separation from air, 1900 kW incl O2 compressors 1 & 2
10	O2 Compressor #1 (incl in Oxygen Plant)	1	264 BHP	Pi=30 psia, Po=160 psia, 2.23 lb/sec, 2 stage reciprocating, includes intercooler
11	O2 Compressor #2 (incl in Oxygen Plant)	1	250 BHP	Pi=160 psia, Po=1400 psia, 1.73 lb/sec, 2 stage reciprocating, includes intercooler
13	Turbine Exhaust Condenser	1	6'D x 27'L	Heat Duty =34,472,630 BTU/hr, Surface Area=14,934 ft^2, ACFM in=167,598, ACFM out=16,321, CW=4596 gpm, Carbon steel shell, Stainless steel tubes
13A	De-entrainment vessel	1	4'D x 8'H	ACFS=272, T=100°F
13B	Condensate Pump	1	2 BHP	71 gpm, P=1.9 psia, T=100°F
15	Feedwater Pump	1	75 BHP	60 gpm, Pi=30 psia, Ti=100°F, Po=1500 psia
17	Preheater Exchanger	1	5'D x 24' L	Surface area=9,796 ft^2, ACFS out=1,713, carbon steel shell, stainless steel tubes, Heat Duty=6,940,512
18	CO2 Compressor #1	1	951 BHP	Pi=1.9 psia, Po=162 psia, 2 lb/sec, 6 stage centrifugal, stl steel, includes intercoolers
26	CO2 Compressor #2 (at oil field)	1	185 BHP	Pi=162 psia, Po=1,000 psia, 1.9 lb/sec, stainless steel, includes intercooler
40	CO2 Accumulator (at oil field)	1	3'-6" D x 7'-0" H	Stainless Steel, 1,000 design pressure.
30	Cooling Tower	1	14'Lx24'Wx20'H	Flowrate=5300 gpm, Hot Water T=95°F, Cold Water T=80°F, Wet Bulb=70°F, Fan HP=75
16	Cooling Tower Water Pump	1	110 BHP	5,300 gpm
31	Condensate Water Treatment Unit	1		
32	Controls and Instrumentation	1		
33	Switch Gear	1		
34	Transformer	1		
35	Data Aquisition System	1		
36	Natural Gas Surge Vessel	1	3'-6" D x 10'-6"H	Carbon Steel
37	Condensate Tank	1	4'D x 12'L	Stainless Steel
38	Condensate Tank Bleed Pump	1	0.5 BHP	11.2 gpm
39	Cooling Tower Water Blowdown Pump	1	1 BHP	25 gpm

Appendix B.3

Pre-Conceptual Cost Estimate Bases and Details

for

Zero Emission Steam Technology Research Facility

A. PROJECT DATA

Project Location: Lawrence Livermore National Laboratory (LLNL)
Livermore, California.

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Project Scope: The project consists of engineering, procurement and construction (EPC); and operation for a Zero Emission Steam Technology (ZEST) Research Facility.

Type of Estimate: Pre-conceptual level cost estimate.

Pricing Level: Third Quarter of FY 2000.

B. CAPITAL COST ESTIMATE BASIS

Scope Definition
The scope for this estimate is described as follows:

- Preconceptual design information of the ZEST Research Facility based on Clean Energy Systems, Inc. (CES) and LLNL input
- Preliminary 8 1/2”x11” sketches and equipment list for ZEST Research Facility, gas pipeline and injection well systems:
  - Process Flow Diagrams
  - Equipment List
  - Process Building Layout
  - Site Facilities Layout
  - Pipeline and Well Systems

Process equipment

Process equipment estimate is based on the equipment list developed in the design study. Budget prices were obtained for most of the commercially available equipment, such as compressors and cooling tower, with the costs of other equipment estimated using previous estimates for similar equipment as a guide, current estimating manuals, and in-house data bases.

Cost of turbine is estimated from unit cost of MW based on historical cost data. Cost of gas generator is provided by CES.

Cost estimate for the oxygen plant is based on subcontract with budget price quoted from vendors.

Cost of process control is estimated as a factor equal to 15% of the process equipment cost.

Process Facilities

Process facilities include the process building and pad for the oxygen plant. The Process Building is a light structure metal building on a concrete pad. Building quantities are estimated based on similar commercial light structure.

LLNL Site Support Facilities

Support facilities at the LLNL site include the engineering/control building, and yard equipment. The engineering and control building is a prefab modular building. The yard equipment includes cooling tower pad and site security fence.

Site Improvement

Site improvement cost includes costs for site demolition and site preparation and costs for yard electrical switchgear, duct bank, substation, fire alarm, and utilities tie-in to the site, their design cost, and the costs for licensing and permits. The site improvement cost is furnished by LLNL.

Pipeline and Injection Well Systems

Cost for the CO2 pipeline is furnished by LLNL. Costs for the injection well and monitoring wells are furnished by CES.

Oil Field Facilities

Oil field facilities include the injection pump station with final-stage compressors and monitoring stations. The injection pump station and monitoring stations are metal shed on a concrete pad with a security fence.

Quantity Development and Pricing

Quantities were factored based on building sizing from the estimates for similar facilities, and priced on current pricing levels.

Manual Labor
Davis-Bacon manual labor rates for San Francisco Bay area were used. The Workers' Compensation Insurance rates are included in the wage rates. A standard 40 hour work week was used.

State Sales Tax
A sales tax of 8.25% is included for materials and equipment.

Distributable (General Conditions), Overhead and Profit

Distributable costs include temporary construction facilities, construction equipment, tools, materials, and other distributable support and non-manual labor costs, and field office costs. The distributable and construction contractor's overhead and profit is factored at 30% of the direct construction costs, and at 15% of the subcontract equipment. These factors are based on recent evaluation of industrial rates.

Contractor's bond is calculated at 1% of total construction cost.

Construction management

Construction management costs, including the construction manager's overhead and profit, was included at 10% of the construction contractor's costs.

Architect-engineering, and procurement

Architect-Engineer's design and construction support costs include all functions such as engineering management, project control, all discipline engineering, documentation, quality control, procurement, and support services. The costs were factored at 20% of the field costs for construction excluding subcontract items.

Project management

Project management costs are factored at 7.5% of the field costs.

Escalation

Costs are estimated at 3rd Quarter of FY 2000 level. Escalation of capital cost to midpoint of construction (March 2004) is also reported with an escalation rate of 10.01% based on DOE's cost index.

Contingency

A 35% contingency allowance is included in the ZEST capital cost.

Exclusions

1. Cost of land lease of the oil field
2. Research and development costs
3. Royalties
4. DOE Oversight
5. Salvage value from the DC Power Supply Area demolition
6. Facilities removal and site restoration at the LLNL site or oil field after project completion.

C. OPERATING COST ESTIMATE BASIS

The operating cost estimate includes consumables, utilities, operating personnel wages, and operating material expenditures for the ZEST Research Facility operations after plant construction completion.

Consumable Material Cost

Cost of consumable material for process operations, such as natural gas, is based on current LLNL rates charged to laboratory program. Electricity is based on 4.6 cents per kWh. Natural gas is based on 26 cents per therm unit.

Cost for cooling tower water system treatment chemicals is based on NALCO Chemical Co. quotation for treating the makeup water. This includes all the additives and inhibitors and rental instrument for the package unit.

Utilities and Services Cost

The operating costs for utilities and services are calculated using the actual rate in the plant site. Basis for these costs are calculated electric power needed to operate the facility.

A laboratory facility charge based on buildings square footage is included for facility maintenance. Process equipment maintenance cost is not included. Costs for water and sanitary sewer are from G&A expenses and not included in the estimate.

Labor Cost

The plant will be manned by a combination of research staff and manual operators. For the purposes of this study, it is assumed that the plant operation will be supplemented by two full-time operators. The operators will work a normal 40 hour workweek. Wages for manual operator employee including fringe benefits are based on LLNL wage rate.

Revenue

Revenue from the sales of electricity generated is based on 3 cents per kWh. The revenue is credited to offset the operation cost. Potential revenue from CO2 sales is not considered.

Exclusions

The research staff is excluded from the operating cost estimate. No contingency allowance is included.

Job 23386-910, 5MW ZEST Research Facility
(ZEST = Zero Emissions Steam Technology)
At LLNL Site, Livermore, California

Table 1
Total Engineering and Construction Capital Cost
(in 3rd Q / FY2000 Dollars)

Facility / Cost Items	Subtotal	Contingency 35.0%	Total
Process Equipment	27,045,000	9,466,000	36,511,000
Process Facilities	2,587,000	905,000	3,492,000
Support Facilities	1,259,000	441,000	1,700,000
Oil Well Facilities	752,000	263,000	1,015,000
Sub-total Construction	**31,643,000**	**11,075,000**	**42,718,000**
Process Equipment	2,983,000	1,044,000	4,027,000
Process Facilities	407,000	142,000	549,000
Support Facilities	217,000	76,000	293,000
Oil Well Facilities	130,000	46,000	176,000
Sub-total Engineering	**3,737,000**	**1,308,000**	**5,045,000**
Total	**35,380,000**	**12,383,000**	**47,763,000**

Job 23386-910, 5MW ZEST Research Facility
(ZEST = Zero Emissions Steam Technology)
At LLNL Site, Livermore, California

Table 2
Process equipment

WBS	Facilities / Cost Items	Quantity	Unit	Manhours Hour	Materials	Labor	S/C	Tax On Mat'l 8.25%	Sub-total	Contingency %	Contingency $	Total
	Direct costs:											
	Zero Emissions Equipment											
	Process equipment	29	ea	12,740	9,020,000	562,000	7,500,000	744,000	17,826,000			
	Total direct costs	1	ls	12,740	9,020,000	562,000	7,500,000	744,000	17,826,000			
	Field indirect costs:	30% of direct costs			2,706,000	168,000		223,000	3,098,000			
	(Include Distributable field costs and contractors' overhead & profit)	15% of subcontract equip costs					1,125,000		1,125,000			
	Sub-total contractor's costs				11,726,000	730,000	8,625,000	967,000	22,049,000			
	Contractor's bond	1% of S/T Contr's Cost			117,000	7,000	86,000	10,000	220,000			
	Total contractor's Field costs				11,844,000	737,000	8,711,000	977,000	22,269,000			
	Construction management	10% of Contractor's field cost			1,184,000	74,000	871,000	98,000	2,227,000			
	Total field costs				13,028,000	811,000	9,582,000	1,075,000	24,496,000			
	A/E costs: (Title I, II &III)	20.0% of field mat'l & labor costs			2,606,000	162,000		215,000	2,983,000			
									27,479,000			
	Project management (Excludes DOE)	7.5% of total field costs							2,061,000			
	Sub-total								29,540,000			
	Escalation from FY3Q/00 to											
	Total								29,539,875			
	Process Equipment:											
	Engineering								2,983,000		1,044,000	4,027,000
	Fabrication								9,764,000	35.0%	3,418,000	13,182,000
	Installation								16,793,000	35.0%	5,877,000	22,670,000
	Certification and Test	5% of Fabrication							488,000	35.0%	171,000	659,000
	Total								30,028,000		10,510,000	40,538,000

Note (1): Applied to Labor Cost Only

Table 3
Process Facilities

Job 23386-910, 5MW ZEST Research Facility
(ZEST = Zero Emissions Steam Technology)
At LLNL Site, Livermore, California

WBS	Facilities / Cost Items	Quantity	Unit	Manhours Hour	Materials	Labor	S/C	Tax On Mat'l 8.25%	Sub-total	Contingency %	Contingency $	Total
	Direct costs:											
	Process Building (140'l, 50' x 30'h)	7,000	sf	17,139	630,000	706,000	238,000	52,000	1,626,000			
	Oxygen Plant (80'x 90') Pad	7,200	sf	655		21,000			21,000			
	Initial Spare --											
	Allow for service mech. equipment	1	lot									
	Total direct costs	14,200	sf	17,794	630,000	727,000	238,000	52,000	1,647,000			
	Field indirect costs: (Include Distributable field costs and contractors' overhead & profit)	30% of direct costs			189,000	218,000	71,000	16,000	494,000			
	Sub-total contractor's costs				819,000	945,000	310,000	68,000	2,141,000			
	Contractor's bond	1% of S/T Contr's Cost			8,000	9,000	3,000	1,000	21,000			
	Total contractor's Field costs				827,000	955,000	313,000	68,000	2,162,000			
	Construction management	10% of Contractor's field c			83,000	95,000	31,000	7,000	216,000			
	Total field costs				910,000	1,050,000	344,000	75,000	2,379,000			
	A/E costs (Title I,II & III)	20.0% of subtotal costs			182,000	210,000		15,000	407,000			
									2,786,000			
	Project management (Excludes DOE)	7.5% of total field costs							209,000			
	Escalation from FY3Q/00 to											
	Total								2,994,000	35.0%	1,048,000	4,042,000
	Process Facilities											
	Engineering (See Engineering Est.)								407,000	35.0%	142,000	549,000
	Construction								2,379,000	35.0%	833,000	3,211,000
	Project Management								209,000	35.0%	73,000	282,000
	Total								2,994,000		1,048,000	4,042,000

Note (1): Applied to Labor Cost Only

6/13/2000
0_EmsnPF.xls

Job 23386-910, SMW ZEST Research Facility

Table 4
Support Facilities

At LLNL Site, Livermore, California

WBS	Facilities / Cost Items	Quantity	Unit	Manhours Hour	Materials	Labor	S/C	Tax On Mat'l 8.25%	Sub-total	Contingency %	Contingency $	Total
	Direct costs:											
	Site Improvement -allow for Security Fence	1,000	lf				23,000		23,000			
	Support Facilities :-											
	Warehouse / Shop (30' x 100' x 20' h)	N/A	sf									
	Cooling Tower, 30' x 30' x(24") Concrete Pad	900	sf	1,309	24,000	54,000		2,000	80,000			
	Engineering / Control Building w/ HVAC	3,200	sf	7,711	363,000	277,000	27,000	30,000	697,000			
	Substation / switchgear, 40' x 40' pad, By LLNL		sf									
	Total direct costs	4,100	sf	9,020	387,000	331,000	50,000	32,000	800,000			
	Field indirect costs: (Include Distributable field costs and contractors' overhead & profit)	30%	of direct costs		116,000	99,000	15,000	10,000	240,000			
	Sub-total contractor's costs				504,000	430,000	65,000	42,000	1,040,000			
	Contractor's bond	1%	of S/T Contr's Cost		5,000	4,000	1,000		10,000			
	Total contractor's Field costs				509,000	435,000	66,000	42,000	1,051,000			
	Construction management	10%	of Contractor's field cost		51,000	43,000	7,000	4,000	105,000			
	Total field costs				559,000	478,000	72,000	46,000	1,156,000			
	A/E costs (Title I, II &III)	20.0%	of subtotal costs		112,000	96,000		9,000	217,000			
	Sub-total costs								1,373,000			
	Project management (Excludes DOE)	7.5%	of total costs						103,000			
	Escalation from FY3Q/00 to											
	Total								1,476,000	35.0%	516,000	1,992,000
	Site Improvement and Support Facilities											
	Engineering (in Engineering package)								217,000	35.0%	76,000	293,000
	Construction								1,156,000	35.0%	405,000	1,561,000
	Project Management								103,000	35.0%	36,000	139,000
	Total								1,476,000		516,000	1,992,000

Note (1): Applied to Labor Cost Only

Table 5
Oil Well Facilities

Job 23386-910, 5MW ZEST Research Facility

At LLNL Site, Livermore, California

WBS	Facilities / Cost Items	Quantity	Unit	Manhours Hour	Materials	Labor	S/C	Tax On Mat'l 8.25%	Sub-total	Contingency %	Contingency $	Total
	Direct costs:											
	Site Improvement - for Site Clearing and Security Fences.	0.32	acres				27,000		27,000			
	Support Facilities :											
	Injection Pump Station: 30' x 30' x 30'h (Pre-engin bldg) 1EA	400	sf	1,019	258,000	41,000		21,000	321,000			
	Monitoring Wells Stations: 15' x 15' x 12'h (Pre-eng bldg). 4 EA	900	sf	1,766	53,000	72,000		4,000	130,000			
	Total direct costs	1,300	sf	2,785	311,000	113,000	27,000	25,000	478,000			
	Field indirect costs: (Include Distributable field costs and contractors' overhead & profit)	30% of direct costs			94,000	34,000	8,000	8,000	143,000			
	Sub-total contractor's costs				405,000	147,000	35,000	33,000	621,000			
	Contractor's bond	1% of S/T Contr's Cost			4,000	1,000			6,000			
	Total contractor's Field costs				409,000	149,000	36,000	34,000	627,000			
	Construction management	10% of Contractor's field cost			41,000	15,000	4,000	3,000	63,000			
	Total field costs				450,000	163,000	39,000	37,000	690,000			
	A/E costs (Title I, II & III)	20.0% of subtotal costs			90,000	33,000		7,000	130,000			
	Sub-total costs								820,000			
	Project management (Excludes DOE)	7.5% of total costs							62,000			
	Escalation from FY3Q/00 to											
	Total								882,000	35.0%	309,000	1,190,000
	Site Improvement and Support Facilities											
	Engineering (in Engineering package)								130,000	35.0%	46,000	176,000
	Construction								690,000	35.0%	242,000	932,000
	Project Management								62,000	35.0%	22,000	83,000
	Total								882,000		309,000	1,190,000

Note (1): Applied to Labor Cost Only

Summary of LLNL Site Preparation and CO2 Pipeline Costs for ZEST Research Facility

Project Title: ZEST - RF, Rev. # 1

PFN: AET00001
Acct: 1524-91
Date: 19-Jun-00

Requested By: Jim Brady
Estimated By: Jerry L. Cook, Val Arora, M. Erickson

Checked By: JLC
Approved By: (J. L. COOK)

DESCRIPTION	O & C Division	UNIT	Base Utilities	Pipeline	Total
ESTIMATED CONSTRUCTION COST (BID)			$3,853,200	$1,426,300	$5,279,500
UNIVERSITY PRE-PURCHASED MATERIAL / EQUIPMENT		LS	0	0	0
Estimated Contract Duration - Calendar Days			260	155	415
TOTAL ESTIMATED CONSTRUCTION COST			**$3,853,200**	**$1,426,300**	**$5,279,500**
PLANT ENGINEERING SUPPORT COSTS:					
Design (A/E)		LS	0	0	0
Design (PE)		LS	0	0	- 0
Project Management	3.0	LS	115,600	42,800	158,400
Construction Management	2.0	LS	77,100	28,500	105,600
Inspection	2.5	LS	96,300	35,700	132,000
Value Engineering		LS	0	0	0
Documentation Funding	0.1	LS	3,900	1,400	5,300
LLNL Labor & Material / M & O Documentation	0.4	LS	15,400	5,700	21,100
Activation		LS	0	110,000	110,000
		Subtotal:	308,300	224,100	532,400
E/OPC___ PMC___ ISC___ LFC/OFC___		%	76,700	63,600	140,300
		Subtotal:	385,000	287,700	672,700
General And Administrative (G&A) And Security	49.5	%	190,600	88,000	278,600
OTHER SUPPORT COSTS:					
Hazards Control	0.6	LS	23,100	8,600	31,700
Environmental		LS	20,000	40,000	60,000
Protective Services		LS	0	0	0
Program Support Cost		LS	0	0	0
Procurement (MPC)	$2K + 4.0		156,100	59,100	215,200
		Subtotal:	199,200	107,700	306,900
OPC___ PMC___ ISC___ LFC/OFC___		%	3,000	3,400	6,400
		Subtotal:	202,200	111,100	313,300
General And Administrative (G&A) And Security	49.5	%	100,100	55,000	155,100
ESTIMATED SUPPORT COST		LS	877,900	541,800	1,419,700
ESCALATION (SUPPORT COSTS)		LS	0	0	0
CONTINGENCY		LS	0	0	0
		Subtotal All Costs:	4,731,100	1,968,100	6,699,200
LAB DIRECTED RESEARCH & DEVELOPMENT (LDRD)	0.00	%	0	0	0
TOTAL ESTIMATED COST (TEC)			**$4,731,100**	**$1,968,100**	**$6,699,200**

Summary of Oil Field Well Costs for ZEST Research Facility

Five wells need to be drilled and completed for the ZEST power plant research facility. One well is an injection well and the other four wells are observation/monitoring wells. The five wells are identified in Table 1 below. Detailed costs of the wells are shown in the attachments. The cost of drilling and completing the five wells is $2,080,600.

Each well will require a pad, a small building, electric (AC) power, and security fence. The pad and building of the injection well is larger than the pad and building of the four observation wells. The increased building size is due to the need for a housing of a compressor/pump. This unit is required to bring the pressure of the carbon dioxide to the injection pressure.

Each of the four observation/monitoring wells has a casing size of 8 5/8" and depth of 3,200 ft. The surface requirements for each of the four observation/monitoring wells are identical. Electrical power supplied to the building at each of the four observation/monitoring wells should be about 3 KW. This power requirement is based on the use of the well as an observation well, and not as a possible production well.

No personnel will be needed on-site for normal operations. Operating control will be at the LLNL ZEST facility and will require approximately 0.2 FTE. No contingencies are included. Unexpected expenses may occur in the drilling and completion of the wells on account of local subsurface geologic variations. Also, included in the cost summary (and attachment) is the cost of one workover. The workover is included to handle unforeseen difficulties once the wells are placed into operation.

Table 1. Summary of Drilling and Completion Costs

Number of Wells	**Well Type**	**AFE Number**	**Cost**
1	Injection, 2,000 ft	LLNL-1	$351,800
4	Observation, 3,200 ft	LLNL-3	$406,700
		LLNL-3	$406,700
		LLNL-3	$406,700
		LLNL-3	$406,700
1	Workover	LLNL-4	$102,000
	Total Cost		$2,080,600

ZEST RESEARCH FACILITY

ANNUAL OPERATING COST ESTIMATE SUMMARY

		Total ($)
1	Materials	630,240
2	Utilities and Services	703,432
3	Labor	156,000
4	Laboratory Facility Charge	91,800
	Subtotal Annual Operating Cost	1,581,500
5	Revenue from sales of electricity	1,034,800
	Total Annual Operating Cost	546,700

6/29/01